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AAC-TR-08-17**



Hydrodynamic Ram Simulator

**Ronald Hinrichsen
RHAMM Technologies
332 Skyland Dr.
Bellbrook, OH 45305**

**Stephen Stratton
RHAMM Technologies
332 Skyland Dr.
Bellbrook, OH 45305**

**Albert Moussa
BlazeTech
24 Thorndike Street
Cambridge, MA 02141**

**Gangming Zhang
BlazeTech
24 Thorndike Street
Cambridge, MA 02141**

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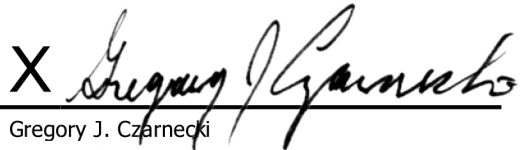
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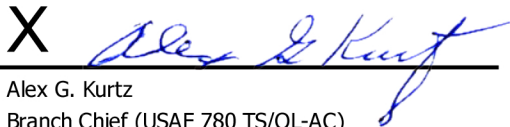
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X 

Ronald L. Hinrichsen
Principal Investigator (RHAMM Technologies, L...

X 

Gregory J. Czarnecki
Project Manager (USAF 780 TS/OL-AC)

X 

Alex G. Kurtz
Branch Chief (USAF 780 TS/OL-AC)

X 

John J. Murphy, Jr.
Technical Director (USAF 780 TS/OL-AC)

X 

Paul C. Ulrich
Flight Chief (USAF 780 TS/OL-AC)

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14. ABSTRACT The objective of this work was to develop a low-cost method of evaluating hydrodynamic ram and blast effects on aircraft materials that is effective for both joint and flat plate testing and able to assess failure properties of both types of structures. The approach was to revise the design of the RamGun test device to avoid previously-discovered shortfalls. This was to be done as follows: 1.)Larger test section to avoid boundary effects,2.) Elimination of internal reflections that confound data, 3.)Tuned pressure pulses that map to specific threats, 4.)Design supported by LSDYNA, 5.)Dem-val tests to verify final design. The effort was piggy-backed onto a Phase II SBIR. The focus of this report is the design support being performed by LSDYNA simulations in support of the SBIR tasks.					
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Symbols

A	=	constant for JWL equation of state
B	=	constant for JWL equation of state
E	=	specific internal energy
P	=	predicted pressure
R_1	=	constant for JWL equation of state
R_2	=	constant for JWL equation of state
$a_0 \dots a_7$	=	constants for Gruneisen equation of state
e	=	specific internal energy
η	=	ρ/ρ_0 ,
μ	=	$\eta-1$
ω	=	constant for JWL equation of state
ρ	=	overall material density
ρ_0	=	reference density (initial density)

Acronyms

ALE	=	Arbitrary Lagrangian Eulerian
CEL	=	Coupled Euler Lagrange
EOS	=	Equation of State
FEA	=	Finite Element Analysis
FEM	=	Finite Element Method
HRAM	=	Hydrodynamic Ram
JASPO	=	Joint Aircraft Survivability Program Office
SBIR	=	Small Business Innovative Research

EXECUTIVE SUMMARY

The objective of this work was to develop a low-cost method of evaluating hydrodynamic ram and blast effects on aircraft materials that is effective for both joint and flat plate testing and able to assess failure properties of both types of structures.

The approach was to revise the design of the Hydrodynamic Ram Simulator test device to avoid previously-discovered shortfalls. This was to be done as follows:

- Include a larger test section to avoid boundary effects
- Eliminate internal reflections that confound data
- Tune pressure pulses that map to specific threats
- Use LSDYNA to support design development
- Conduct dem-val tests to verify final design

The effort by RHAMM Technologies, LLC, was piggy-backed onto a Phase II SBIR that was being done by BlazeTech. This report focuses on design input (via LSDYNA simulations) to the Hydrodynamic Ram Simulator in support of the SBIR tasks.

1.0 Introduction

Ballistic hydrodynamic ram testing of representative structures is expensive and requires large multi-spar wingbox structures to assess/quantify joint resistance to hydrodynamic ram damage. Tooling, materials, fabrication labor, instrumentation, and testing can easily exceed \$250K/box tested. This \$250K investment then allows evaluation of only a single joint design. A representative low-cost method of evaluating joints and assessing high strain rate failure criteria was needed.

A Hydrodynamic Ram Simulator test method was developed under JASPO Task V-1-05 (Dynamic Loading Methodologies) and demonstrated and validated under Task V-4-04 (Joint Resistance to Ram). Although these tasks proved the test method successful, there were limitations. These included limitations on joint specimen size, lack of control of the incident pressure pulse, and pressure reflections from the flared section of the fluid column.

The Hydrodynamic Ram Simulator test method also proved valuable under a Air Force Phase I Small Business Innovation Research (SBIR) program in which the combined effects of blast and fragmentation damage on flat composite plates was investigated. The Phase I SBIR focused on fast running model development, and the Hydrodynamic Ram Simulator was used to study the combined effects. During execution of the SBIR effort, the same limitations that were identified for joint testing were revealed in flat plate tests. Consequently, an Air Force Phase II SBIR was funded that focused on the conversion of the Hydrodynamic Ram Simulator to resolve the limitations. The Air Force Phase II SBIR funding concentrated on Hydrodynamic Ram Simulator conversion for blast/fragmentation studies on flat plates, while this JASPO task (reported herein) ensured that skin-spar joint test capabilities were retained and ideally enhanced.

1.1 Objective and Approach

The objective of the work was to develop a low-cost method of evaluating hydrodynamic ram and blast effects on aircraft materials that is effective for both joint and flat plate testing and able to assess failure properties of both types of structures.

The approach was to revise the design of the Hydrodynamic Ram Simulator test device to avoid previously-discovered shortfalls. This was to be done as follows:

- Include a larger test section to avoid boundary effects
- Eliminate internal reflections that confound data
- Tune pressure pulses that map to specific threats
- Use LSDYNA[1] to support design development
- Conduct dem-val tests to verify final design

The effort by RHAMM Technologies, LLC, was piggy-backed onto a Phase II SBIR that was being done by BlazeTech. This report focuses on design input (via LSDYNA simulations) to the Hydrodynamic Ram Simulator in support of the SBIR tasks.

The specific tasks outlined for the project were:

- o Task 1.1: Design Hydrodynamic Ram Simulator
- o Task 1.2: Evaluate design using LSDYNA
- o Task 1.3: Perform joint analyses using LSDYNA
- o Task 1.4: Perform limited series of skin-spar joint tests to dem-val function of the Hydrodynamic Ram Simulator.
- o Task 1.5: Final Report.

2.0 Task Details and Results

2.1 Design of Hydrodynamic Ram Simulator

At the conclusion of JASPO Task V-1-05 (Dynamic Loading Methodologies), the Hydrodynamic Ram Simulator consisted of two major components, the air gun and the water column. Figure 2.1-1 shows a photograph of the air gun portion of the

Hydrodynamic Ram Simulator, while Figure 2.1-2 shows a photograph of the water column.

In considering the redesign of the Hydrodynamic Ram Simulator, both of these major components were examined.



Figure 2.1-1 Air Gun Portion of the Hydrodynamic Ram Simulator

In examining the water column, the approach was to eliminate the flared section in order to reduce the reflections, while keeping the diameter of the test chamber the same as it currently is (8.5 inches). Furthermore, because of the desire to enhance the test capabilities of the Hydrodynamic Ram Simulator to handle larger, transport class joints, the diameter of the test chamber would most likely be greater by as much as a factor of 2. This would mean that the diameter of the test chamber could possibly be as great as 17.0 inches.

Removing the flare and/or increasing the diameter of the water column would result in a reduction in the peak pressure in the test chamber. Because of this reduction, modifications were considered in the method by which energy was introduced into the

water column as well as changes in the air gun. The following sections describe how these considerations were examined.

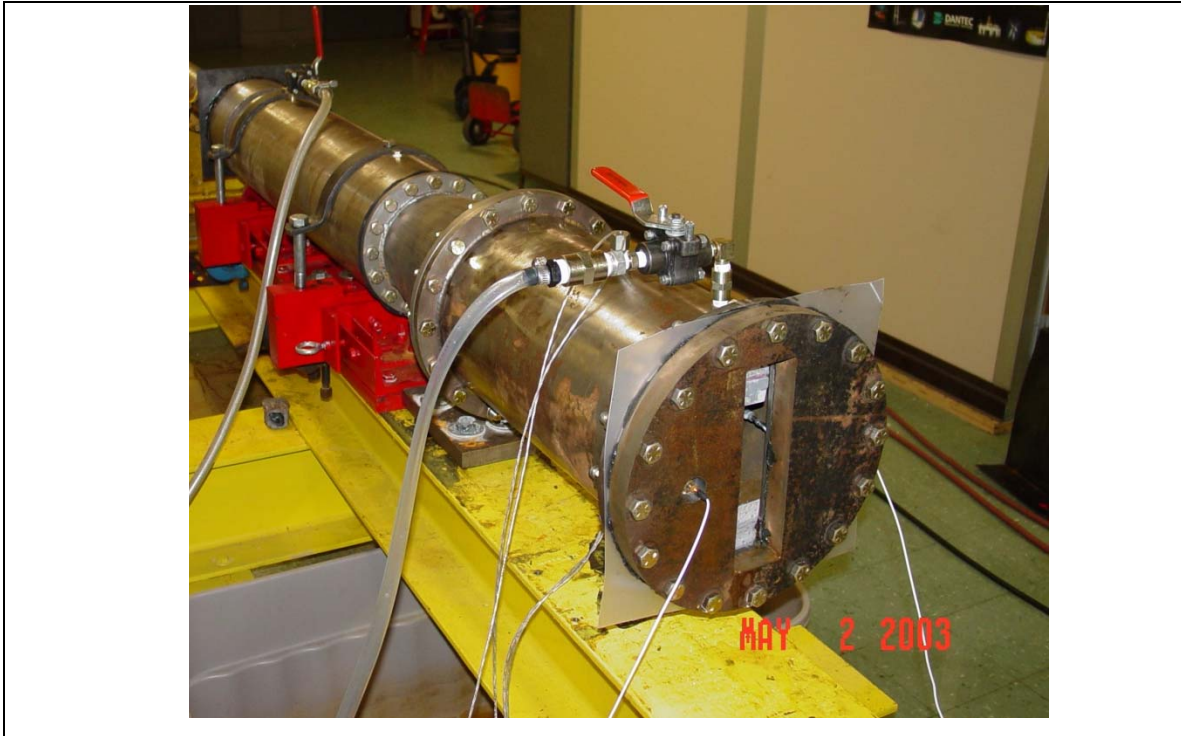


Figure 2.1-2 Water Column Portion of the Hydrodynamic Ram Simulator

2.1.1 Air Gun Considerations

BlazeTech created both 1D and 2D models of the air gun. Figure 2.1-3 shows a comparison between the modeling and test where muzzle speed vs. tank pressure is displayed. This figure tells us that the performance of the current Hydrodynamic Ram Simulator seems to lie between the 1D and 2D models. The decision was made to use the 1D model to perform parametric studies of various parameters that would impact on the performance of the air gun, with the hope that by increasing its performance, the pressure in the water column would also be enhanced.

Figure 2.1-4 shows a cartoon of the 1D model that contains nomenclature of the model as it is used in each of the succeeding plots.

The parameters that were varied were chamber length, chamber diameter, barrel length, barrel diameter, and puck thickness. The term “puck” is used for the Delrin projectile that is propelled by the air gun and impacts the striker plate of the water column. Muzzle (puck) speed, puck kinetic energy, and puck momentum were observed and plotted as a function of tank pressure for most of the parameters varied.

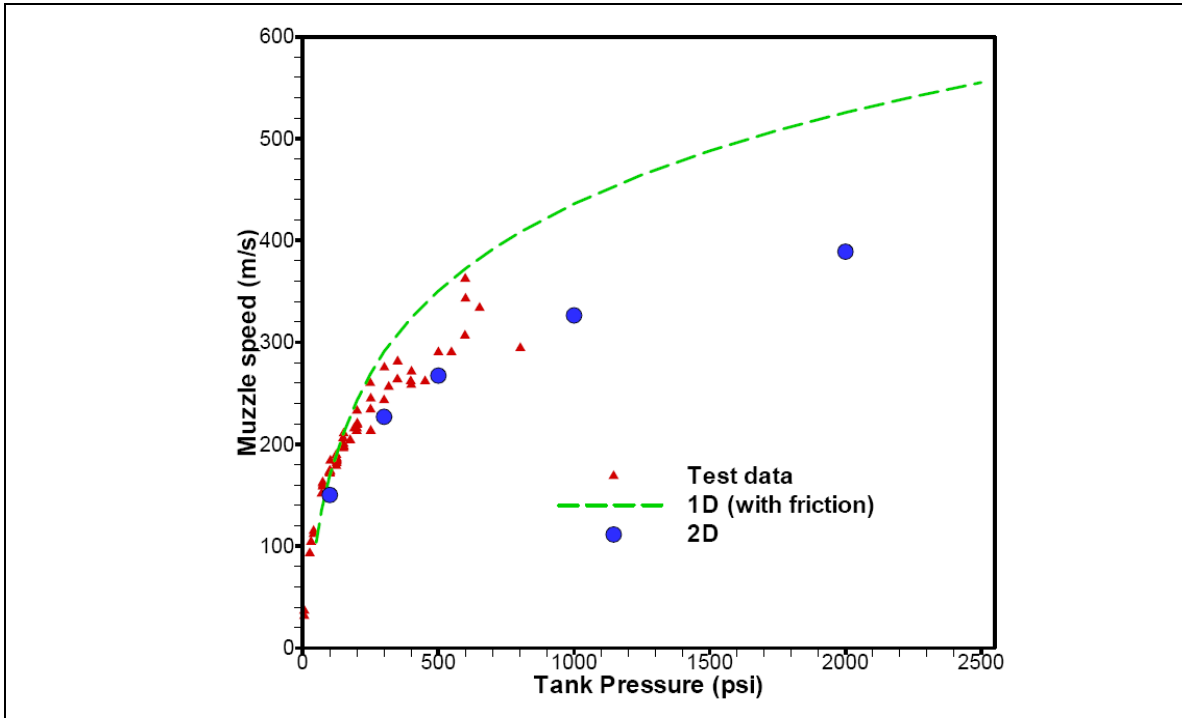


Figure 2.1-3 Comparison Between 1D, 2D Models and Test

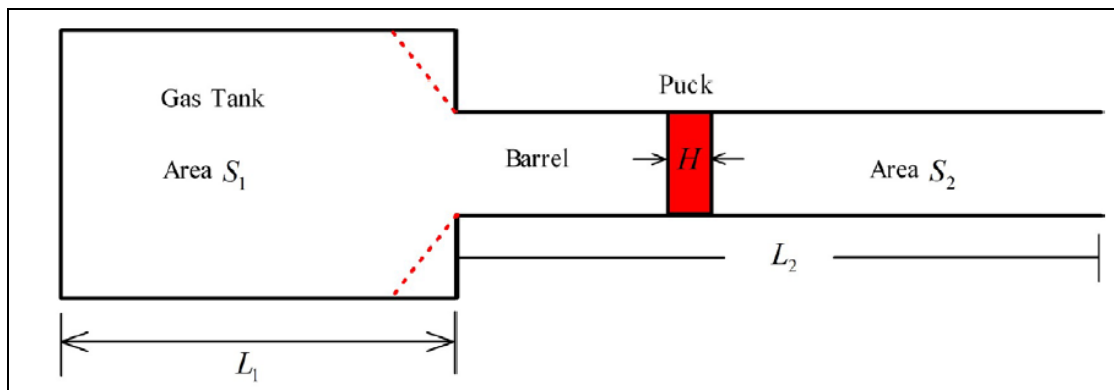


Figure 2.1-4 1D Model Nomenclature

Figure 2.1-5 shows the effect of chamber length on the muzzle speed. This figure shows that varying the chamber length has minor impact on the muzzle speed.

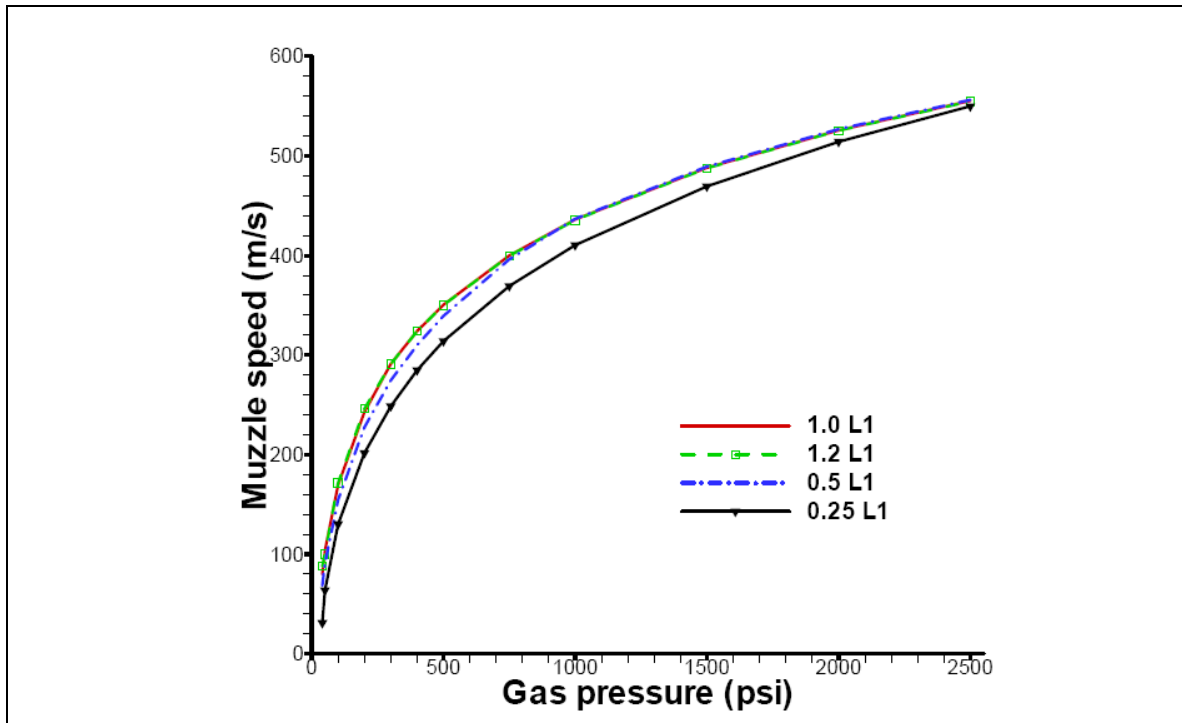


Figure 2.1-5 Effect of Chamber Length on Muzzle Speed

Figure 2.1-6 shows the effect of changing the chamber diameter. Muzzle speed increases as the chamber diameter is increased.

Figure 2.1-7 shows the effect of increasing the length of the barrel. As barrel length is increased, the muzzle speed also increases.

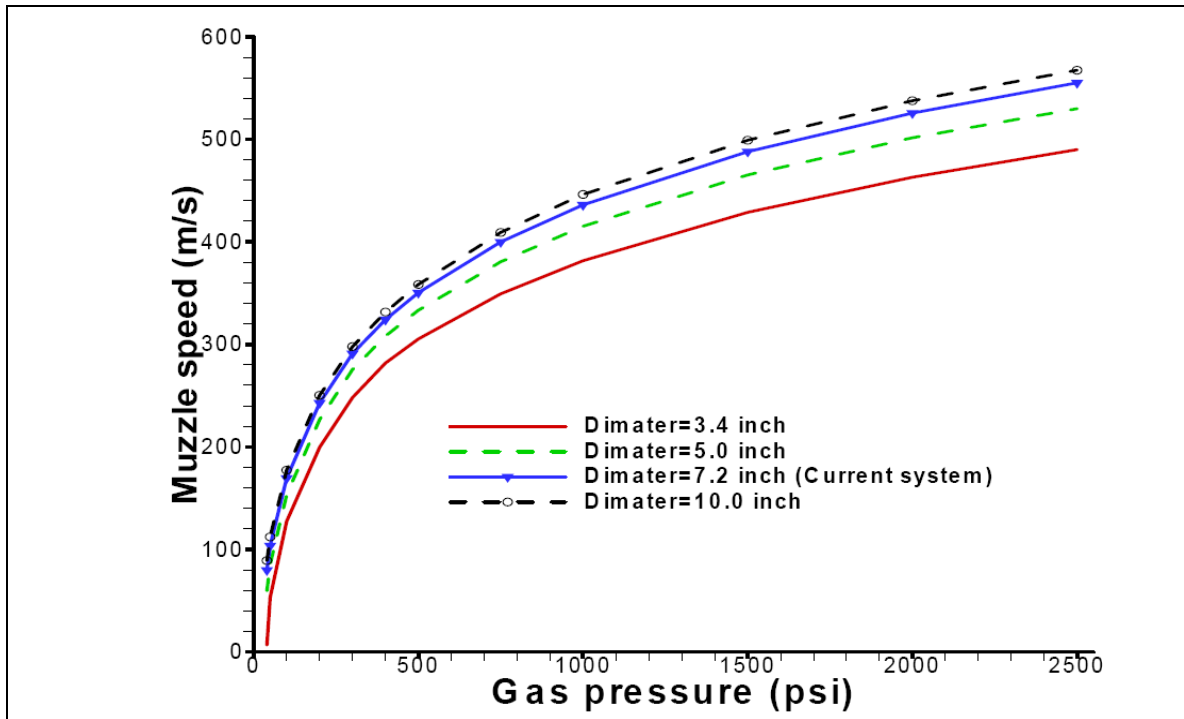


Figure 2.1-6 Effect of Chamber Diameter on Muzzle Speed

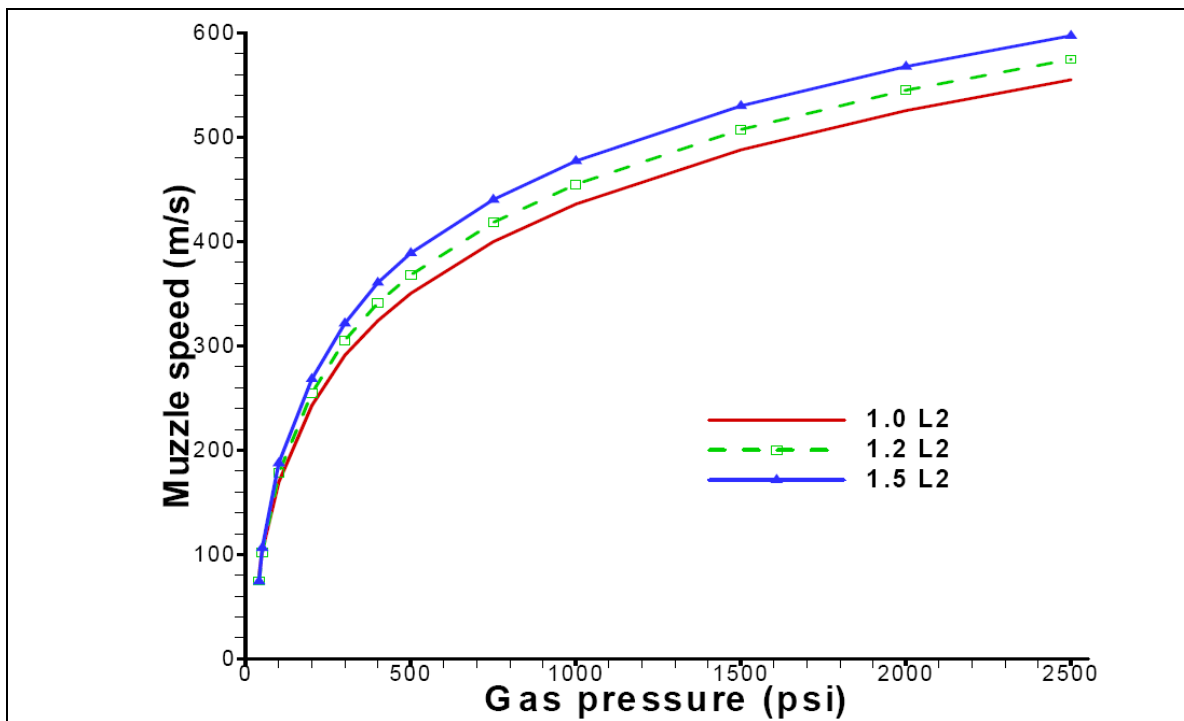


Figure 2.1-7 Effect of Barrel Length on Muzzle Speed

Figure 2.1-8 shows the effect of barrel diameter on muzzle (puck) speed. As barrel diameter is increased, the puck speed decreases slightly.

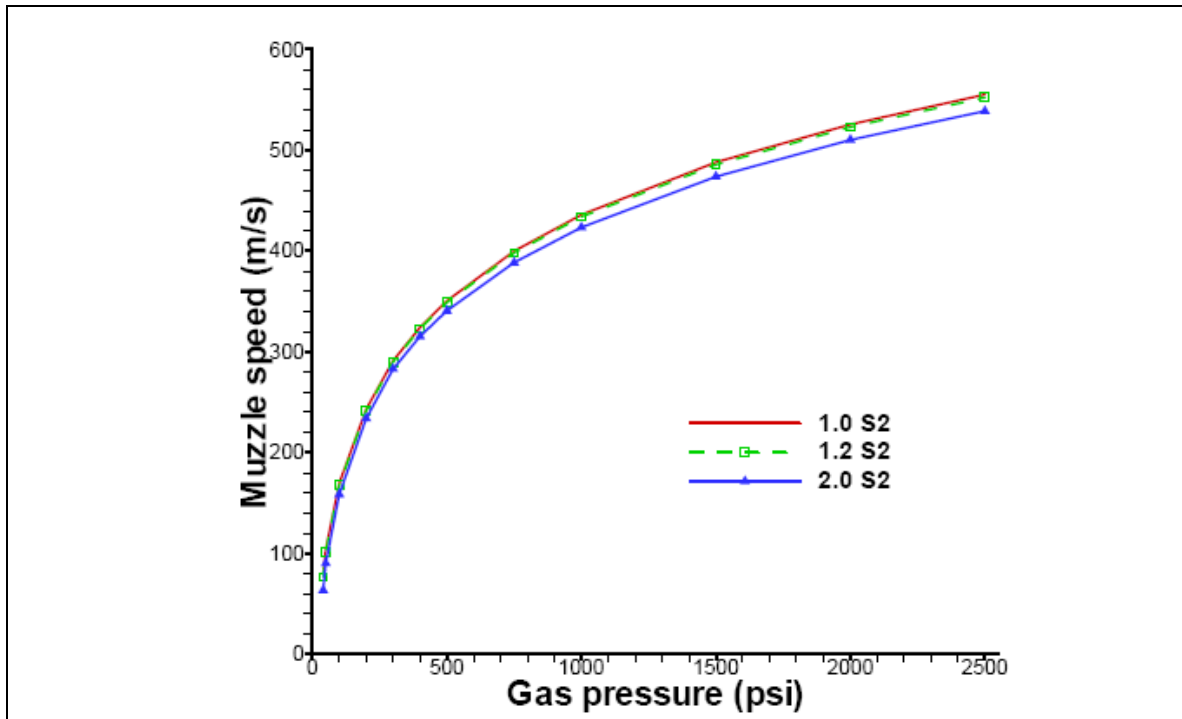


Figure 2.1-8 Effect of Barrel Diameter on Muzzle Speed

Figure 2.1-9 shows the effect of barrel diameter on puck kinetic energy. As the barrel diameter is increased, the mass of the puck also increases. This, in combination with the slight increase in velocity (which is squared in the kinetic energy calculation), causes a significant increase in the puck's kinetic energy.

Figure 2.1-10 shows the effect of barrel diameter on the puck's momentum as it leaves the barrel. As with the kinetic energy increase, the puck's momentum is significantly increased by the increase of barrel diameter.

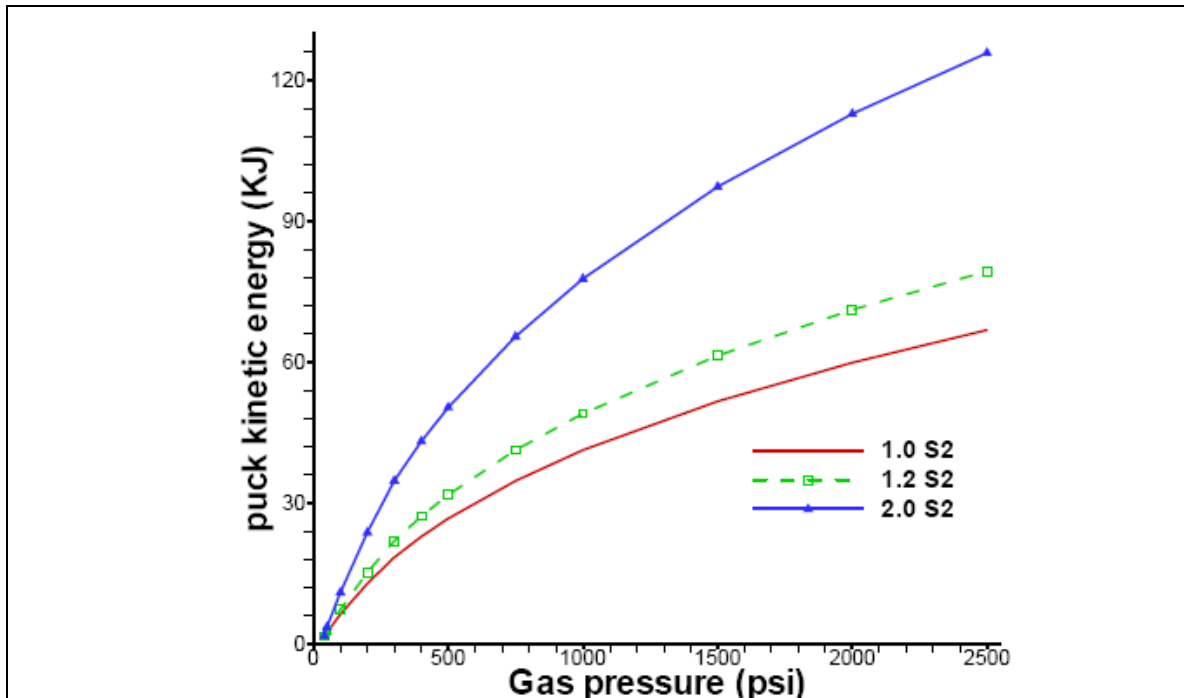


Figure 2.1-9 Effect of Barrel Diameter on Puck Kinetic Energy

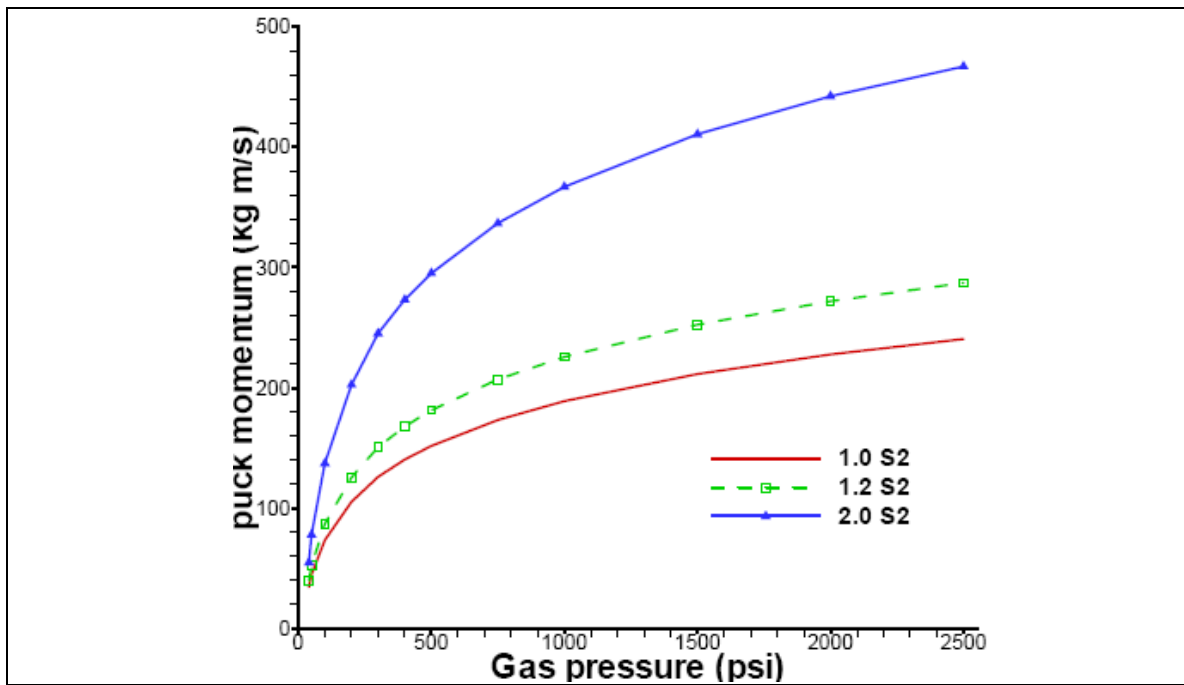


Figure 2.1-10 Effect of Barrel Diameter on Puck Momentum

Figure 2.1-11 shows the effect of puck thickness on the muzzle speed of the puck as it exits the barrel. As the puck thickness is increased, its mass increases, which leads to a decrease in the muzzle speed at barrel exit.

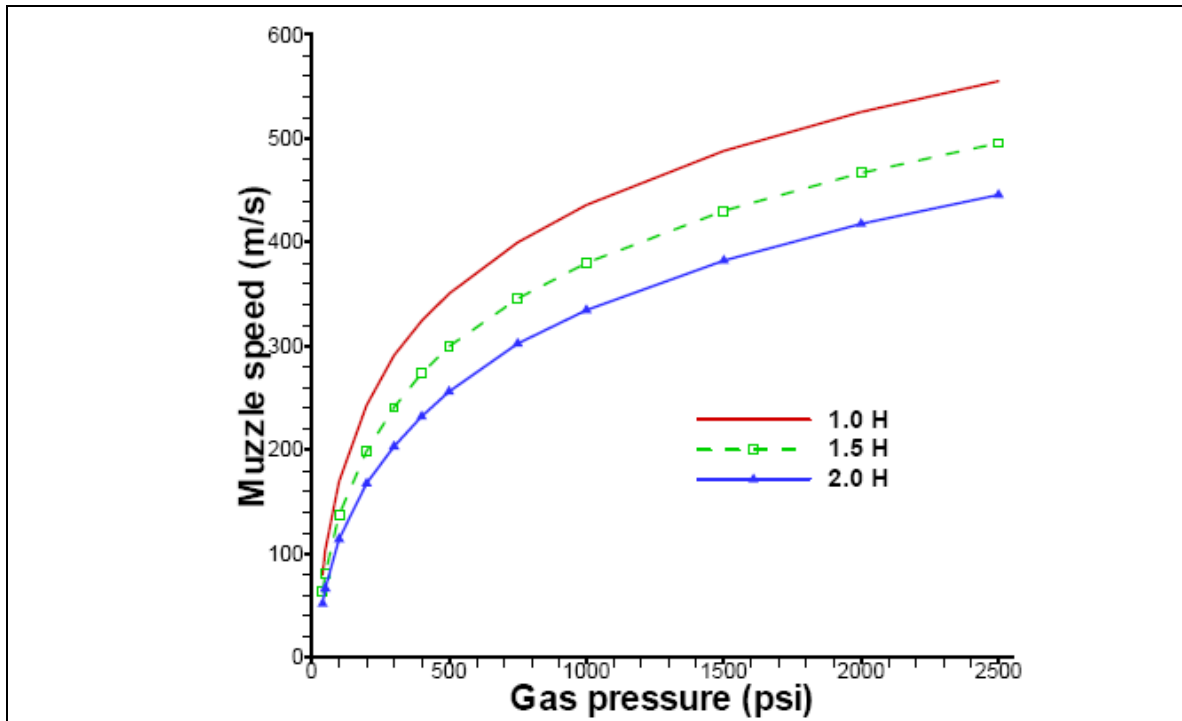


Figure 2.1-11 Effect of Puck Thickness on Muzzle Speed

Figure 2.1-12 shows the effect of increasing the puck's thickness on the kinetic energy of the puck. The kinetic energy is increased as the thickness is increased.

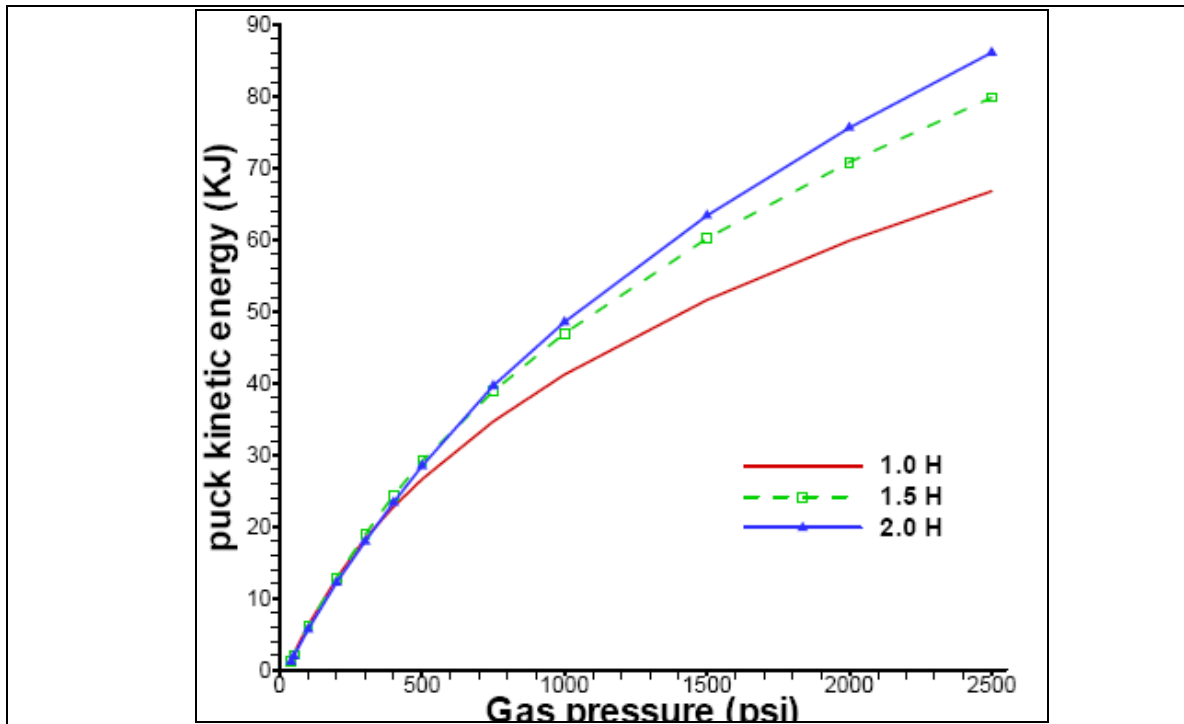


Figure 2.1-12 Effect of Puck Thickness on Puck Kinetic Energy

Figure 2.1-13 shows the effect of increasing the puck's thickness on the momentum of the puck as it leaves the barrel. As with kinetic energy, the momentum is also increased.

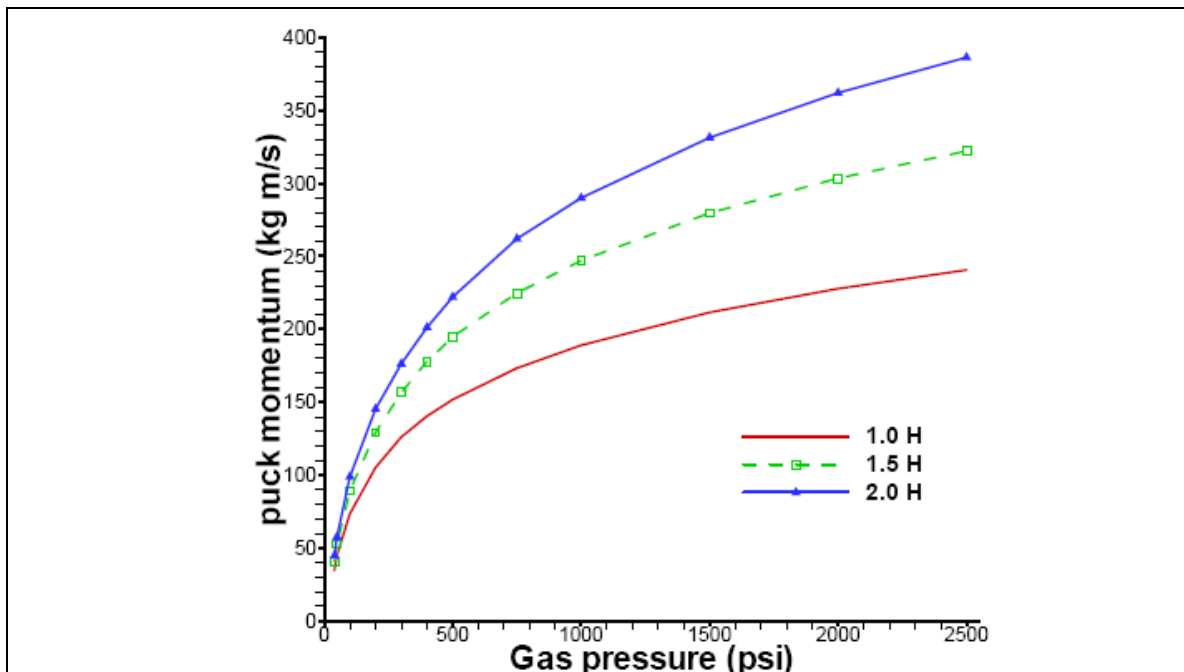


Figure 2.1-13 Effect of Puck Thickness on Puck Momentum

Table 2.1-1 shows a summary of the effects presented above.

Table 2.1-1 Summary of 1D Parametric Study

Outcome	Increase in Dimension of				
	Chamber length	Chamber diameter	Barrel length	Barrel diameter	Puck thickness
Puck speed	↑	↑	↑	↓	↓
Puck momentum	↑	↑	↑	↑	↑
Puck kinetic energy	↑	↑	↑	↑	↑

Based on these observations, the following potential modifications to the air gun were considered, the ultimate purpose being to increase the pressure in the water column.

1. Modifications to increase puck speed, kinetic energy, and/or momentum (in order of preference): Refer to Figure 2.1-4 for a sketch and associated nomenclature.

- increase puck cross-sectional area, S2.
- increase puck thickness, H.
- increase barrel length, L2.
- increase air chamber cross-sectional area, S1.

2. Increasing air chamber length has very little effect on muzzle speed. If necessary, decrease chamber length.

3. Increasing puck cross-section or thickness will affect the impulse magnitude and duration.

4. Design strategy will also depend on cost of modifications.

For each of these possible modifications, the anticipated resulting pressures in the water column would increase. Thus, in each case, the results would be desirable and would increase the amount of energy imparted to the joints in the test chamber. It is also anticipated that the probability would be high that excess energy would be available in testing joints representative of larger transport aircraft.

2.1.2 Water Tank Considerations

One of the drivers in examining the design of the water tank was the desire to increase the diameter of the tank at the test location. The other driver was to remove the flared section that is currently part of the design. The increase in test diameter would facilitate the testing of larger joints and plates, while the elimination of the flared section would reduce the pressure reflections in the tank.

It was felt that increasing the test diameter would result in undesirable reductions of peak pressures in the test section. For this reason, BlazeTech created a 1D model of the water tank and performed parametric studies of how various parameters would effect the pressure pulse. For this study, the puck velocity was held at 984 fps (300mps).

Figure 2.1-14 shows the effect of strike plate thickness on the 1D prediction of pressure pulse. As the thickness is reduced, the peak pressure increases and the decay of pressure occurs over a shorter duration.

Figure 2.1-15 shows the effect of puck thickness on the 1D prediction of the pressure pulse. As the thickness is increased the peak pressure remains constant and the pulse width increases.

Figure 2.1-16 shows the effect of puck diameter on the 1D prediction of pressure pulse. As the puck diameter is increased, the peak pressure increases and the pulse width remains constant.

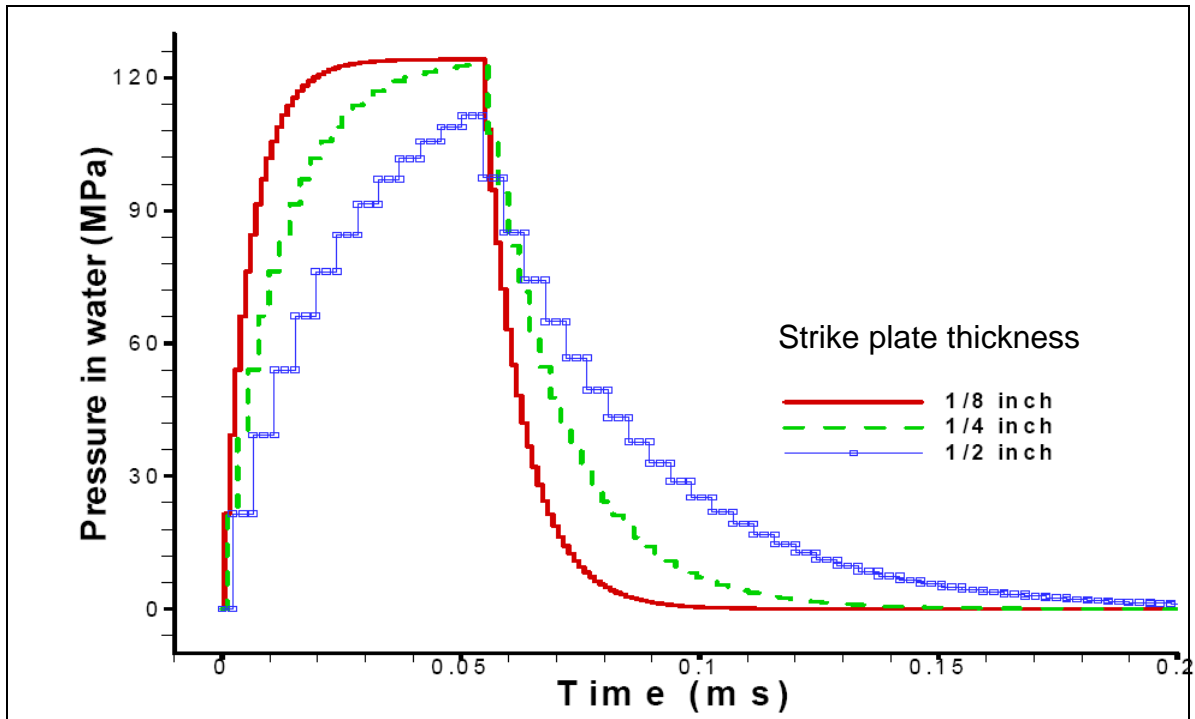


Figure 2.1-14 Effect of strike plate Thickness on Pressure Pulse

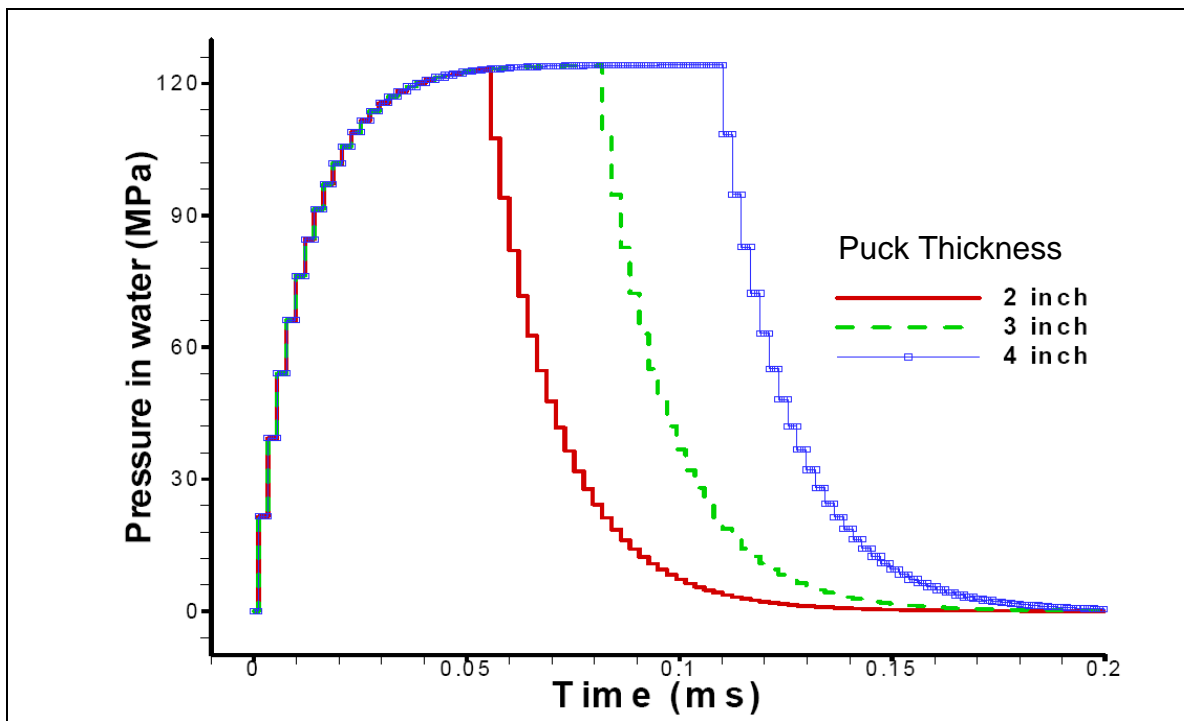


Figure 2.1-15 Effect of Puck Thickness on Pressure Pulse

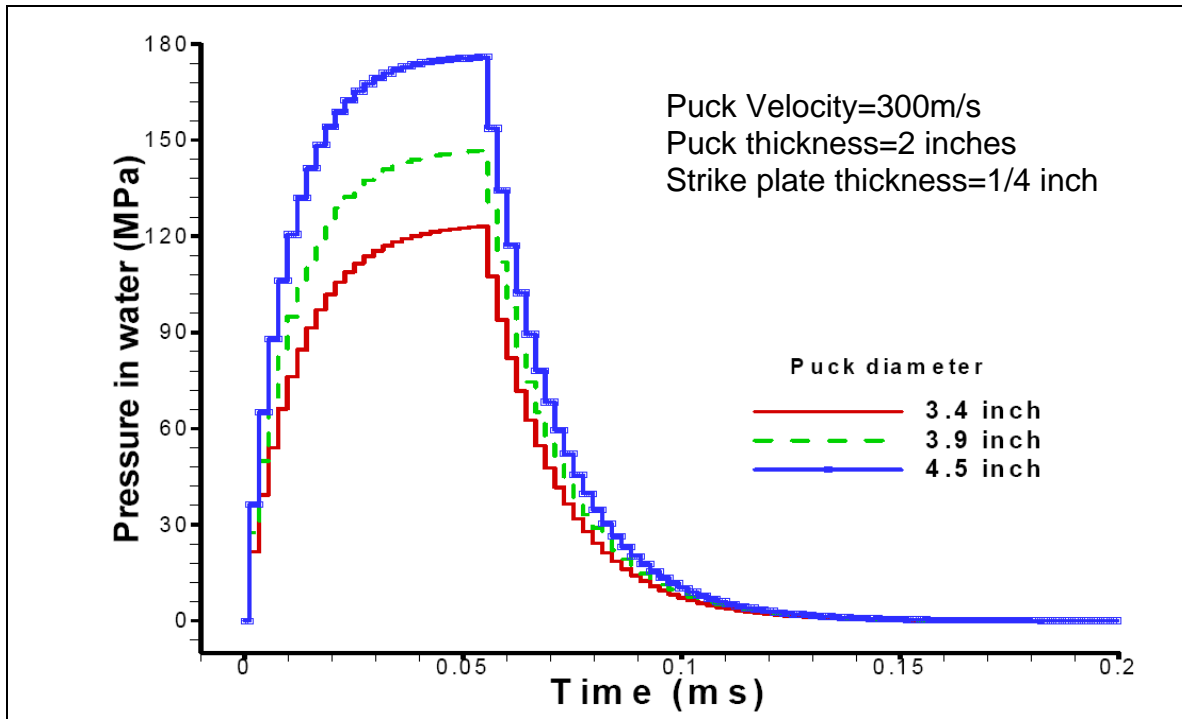


Figure 2.1-16 Effect of Puck Diameter on Pressure Pulse

Based on these 1D studies, it appears that increasing the air gun's barrel diameter and decreasing the strike plate thickness will lead to increases in peak pressure in the test section while maintaining the current pulse width.

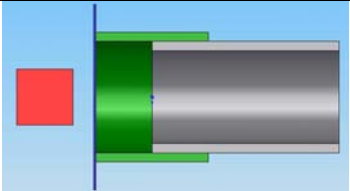
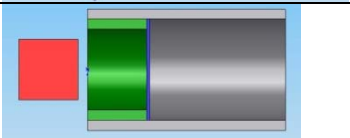
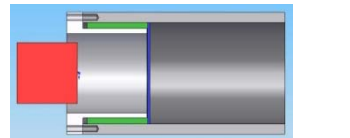
2.2 Evaluation of Designs Using LSDYNA

With 1D calculations in hand, RHAMM Technologies, LLC embarked on a 3D parametric study of two key design features of the water tank. The first was to investigate modifications of the current energy introduction system at the head of the water tank based on suggestions by BlazeTech. The thinking is that, if less energy were absorbed in introducing energy into the water column, more energy would actually go into the raising of the pressures at the test section.

Table 2.2-1 presents definitions and pictorials of the three concepts that were investigated in the 3D parametric study. Note that in each case, the puck diameter and thickness as well as the diameter of the water column were held constant.

In this study, LSDYNA's Coupled Euler-Lagrange (CEL) capability was used. The water in the tank and air surrounding it were modeled in the Eulerian domain, while all the structural components were modeled in the Lagrangian.

Table 2.2-1 Definitions of the Three Concepts for Energy Introduction into the Water Tank

Concept 1 Puck: red Collar: green Strikeplate: blue Tube: grey	Nearly identical to current concept except strike plate has elongated bolt holes to allow for deformation	
Concept 2 Same color scheme	Strike plate is bolted to collar that slides on inside of chamber	
Concept 3 Same color scheme Flange collar: lt grey	Much like concept 2, except with an exterior flange attached to help with leaking, and allows a lightweight collar / strikeplate	

In addition to changing the concept, the strike plate thickness was also varied and peak pressure at a location ahead of the test section were compared. For presentation in this report, the peak pressures were normalized by the peak pressure of the current concept so that comparisons could be readily made.

2.2.1 Common Euler-Lagrange Modeling Practices for LSDYNA

Examination of the LSDYNA code reveals that there are a number of modeling parameters that must be considered. These include the modeling of the fluids (water and air) and the structure. The following subsections summarize those practices that are commonly used. [Note that at the time of this report release, the current version of LSDYNA is 971, however, version 970 was used for all of this work, because RHAMM's experience with the code showed that 970 was more stable (at least during the execution of this project).]

2.2.2 Common Practices for Modeling Air

Air is generally modeled in one of two different ways using a gamma law. The first technique is a perfect gas equation of state given by:

$$P = (\gamma - 1)\rho e \quad (2.2.2-1)$$

with the material properties for air presented in Table 2.2-2.

Table 2.2-2 Properties and Gamma EOS Coefficients for Air

Air Material Properties	Polynomial Equation Coefficients
$\rho_0 = 1.0\text{E-}07 \text{ lb}_\text{f}\text{-s}^2/\text{in}$	$\gamma = 1.4$

The second is the polynomial equation of state and is given by:

$$P = a_0 + a_1\mu + a_2\mu^2 + a_3\mu^3 + (a_4 + a_5\mu + a_6\mu^2 + a_7\mu^3)\rho_0 e \quad (2.2.2-2)$$

where: P = pressure,

ρ = density,

ρ_0 = reference density (initial density),

$\eta = \rho/\rho_0$,

$\mu = \eta - 1$,

e = specific internal energy, and

a's are constants.

For air, the constants need to be set so that $a_0 = a_1 = a_2 = a_3 = a_6 = a_7 = 0$ and $a_4 = a_5 = (\gamma - 1)$. With the coefficients defined in this manner, the polynomial equation of state becomes Equation 2.2.2-1. With this option, both the initial density, ρ_0 , and γ are input directly with the values presented in Table 2.2-2.

2.2.3 Common Practices for Modeling Water

The two equation of state models commonly used to represent water are the polynomial equation of state (2.2.2-2) and the Gruniesen equation of state. Either model can be used.

In using the polynomial equation of state to model water, all constants are set to zero with the exception of “a₁” through “a₃”. The material properties and polynomial EOS coefficients for water were taken from Reference 46 and are presented in Table 2.2-3.

Table 2.2-3 Properties and Polynomial EOS Coefficients for Water

Water Material Properties	Polynomial Equation Coefficients
$\rho_0 = 1.0\text{E-}04 \text{ lb}_f\text{-s}^2/\text{in}$	$a_1 = 0.316\text{E+}06 \text{ psi}$
	$a_2 = 0.750\text{E+}06 \text{ psi}$
	$a_3 = 3.340\text{E+}06 \text{ psi}$

The Gruniesen EOS for compressed materials is given by:

$$P = \frac{\rho_0 C^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2} \right) \mu - \frac{a}{2} \mu^2 \right]}{\left[1 - (S_1 - 1) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{\mu + 1} \right]^2} + (\gamma_0 + a\mu) E \quad (2.2.3-1)$$

where: P = pressure,

ρ = density,

ρ_0 = reference density (initial density),

$\eta = \rho/\rho_0$,

$\mu = \eta - 1$,

C = velocity,

γ_0 = Gruniesen parameter,

E = internal energy, and

S's and “a” are constants.

The material properties and Gruniesen EOS coefficients for water were taken from the CALE library [50] and are presented in Table 2.2-4.

Table 2.2-4 Properties and Gruniesen EOS Coefficients for Water

Water Material Properties	Gruniesen Equation Coefficients
$\rho_0 = 1.0\text{E-}04 \text{ lb}_f\text{-s}^2/\text{in}$	$C = 58267 \text{ in/sec}$
Viscosity = $2.57\text{E-}07 \text{ psi-sec}$	$S_1 = 2.56$
	$S_2 = -1.986$
	$S_3 = 0.2268$
	$\gamma_0 = 0.5$

2.2.4 Common Practices for Modeling Structure

The majority of the Hydrodynamic Ram Simulator consists of components that are made of steel. Figure 2.2-1 shows the stress-strain curve that was used for modeling the steel. The puck is made of Delrin material. For Delrin, Young's Modulus, $E = 4.5\text{E}05$ psi, Poisson's ratio, $\nu=0.33$, Yield Strength, $\sigma_y=1.8\text{E}04$ psi, Tangent Modulus, $E_T=1.0\text{E}04$ psi, and Failure Strain, $\epsilon_f=0.6$

Solid elements, with a minimum of 2 layers through the thickness of each component, were used for all of the structural parts. This ensured that bending within any part was accounted for. LSDYNA's single point integration elements were used, with standard hourglass controls imposed to minimize any hourglassing of the elements.

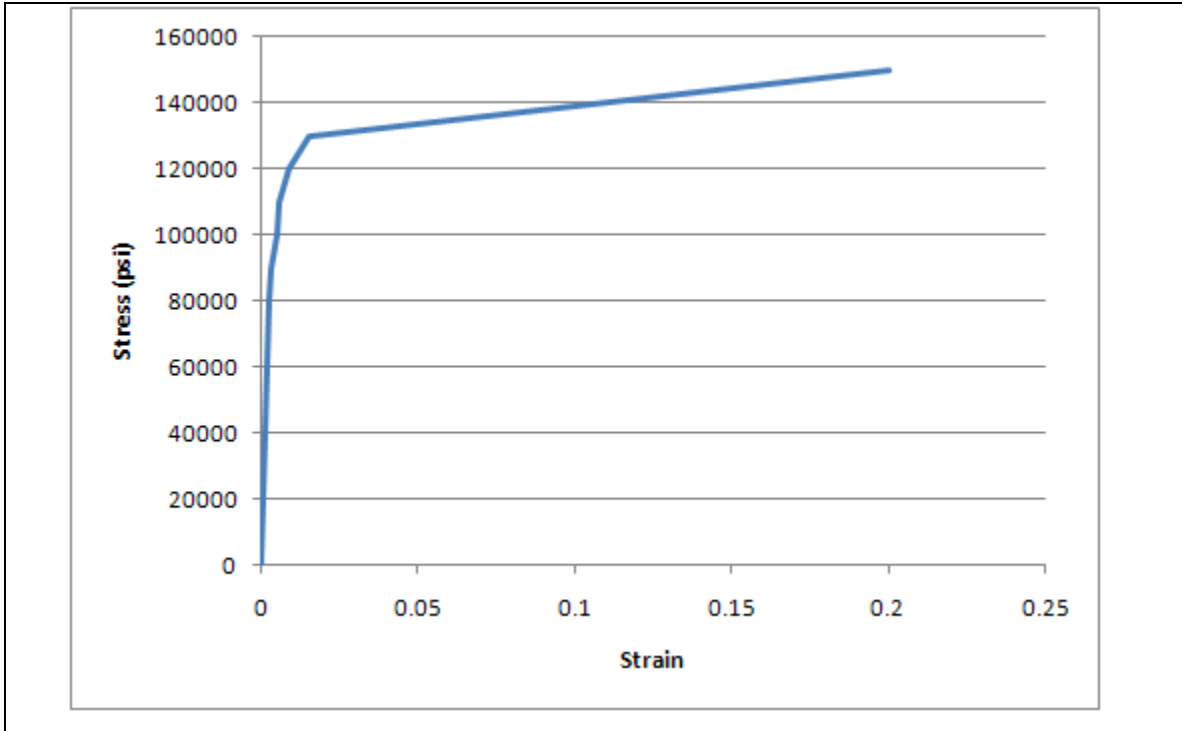


Figure 2.2-1 Typical Stress-Strain Curve for Steel

2.3 Results of the Concept Evaluations

In this parametric study that evaluated the three concepts listed above, the polynomial equation of state was used for both air and water.

Figure 2.3-1 shows the LSDYNA model used to evaluate concept 1. Figure 2.3-2 shows the LSDYNA model used to evaluate concept 2. Figure 2.3-3 shows the LSDYNA model used to evaluate concept 3. Note that, in each of the figures, air surrounding the water tank has been made transparent and the water tank has been cut in half for clarity in viewing the various components.

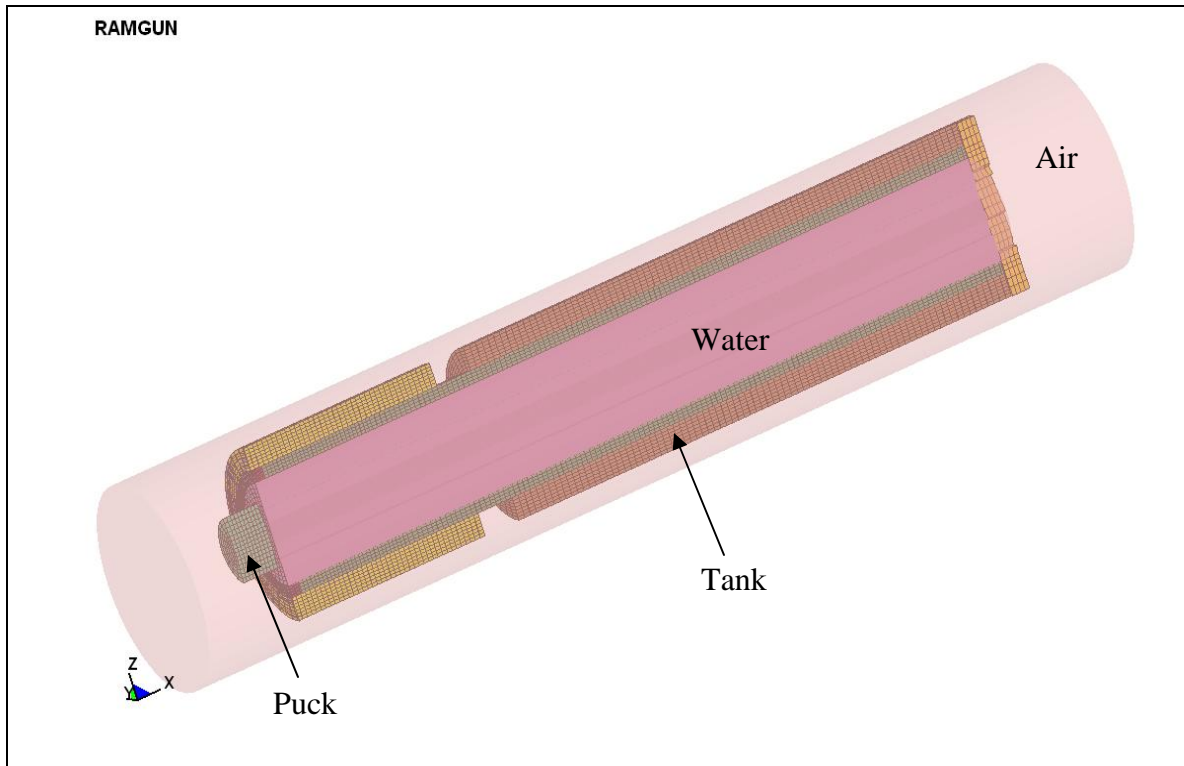


Figure 2.3-1 LSDYNA Model of Concept 1.

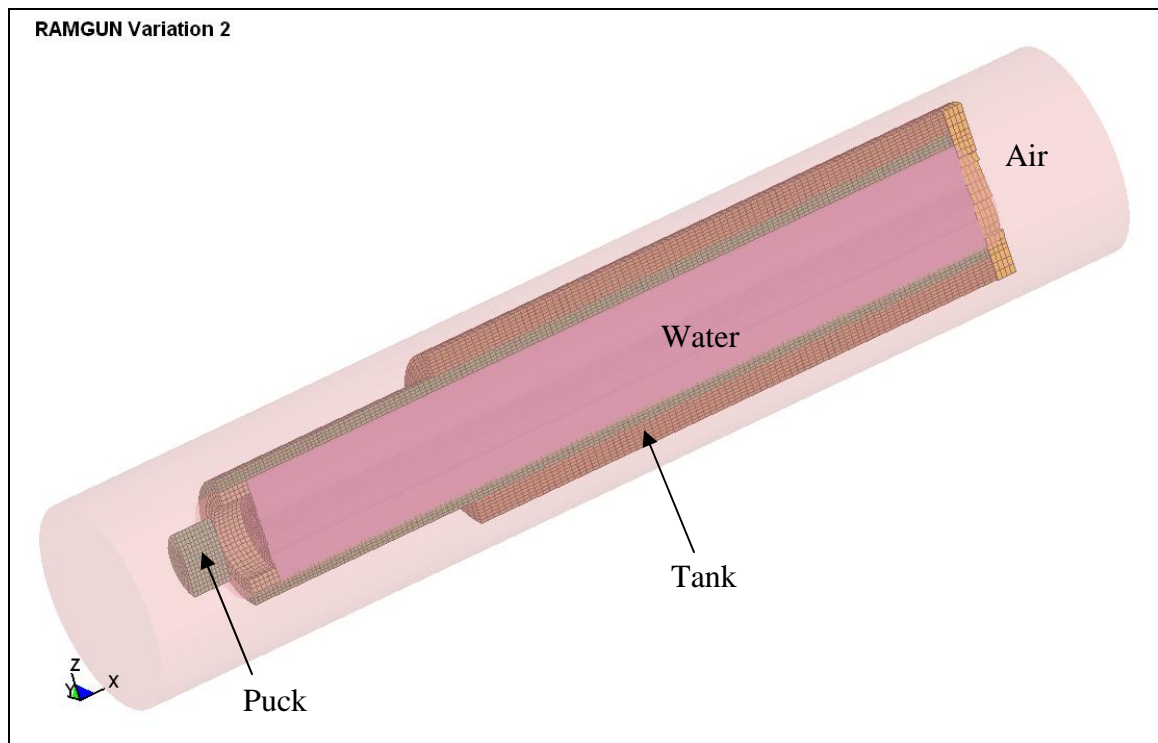


Figure 2.3-2 LSDYNA Model of Concept 2.

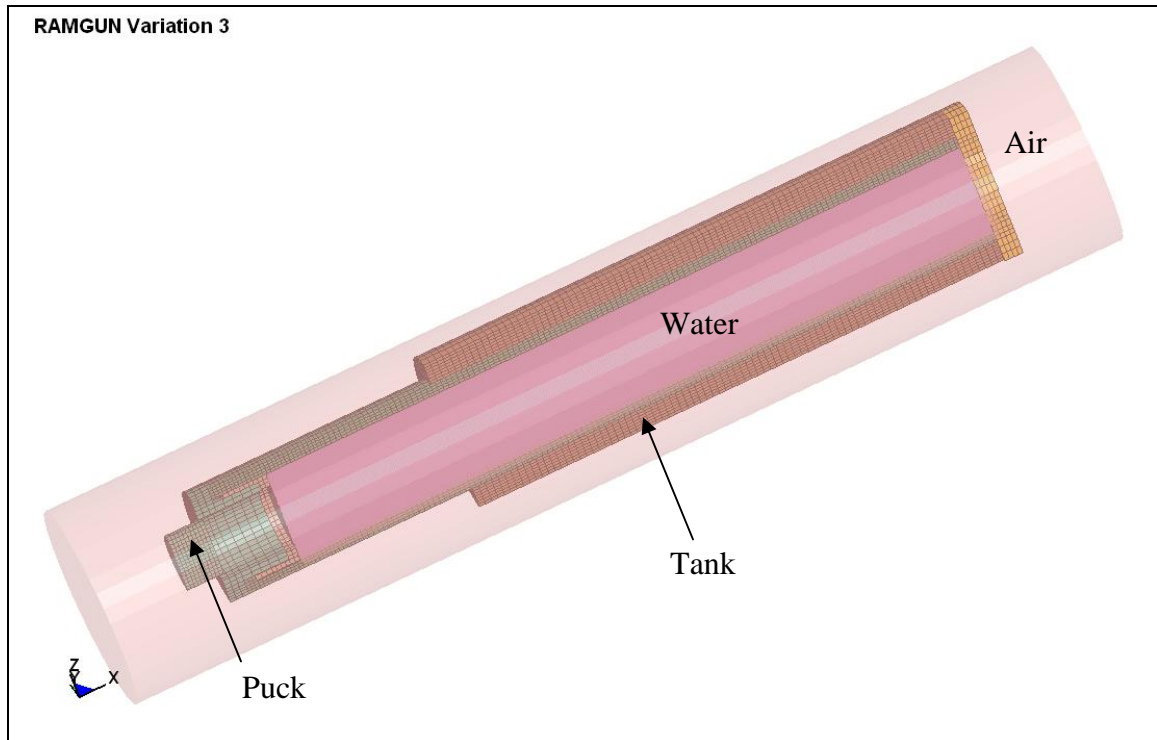


Figure 2.3-3 LSDYNA Model of Concept 3.

Each of the three concepts was run with the puck given an initial velocity of 1000 fps (305 mps). Thickness of the strike plate was varied from its current thickness of 0.125 inches to 0.083 and 0.063 inches.

Figure 2.3-4 shows a chart depicting the normalized pressure as concept and strike plate thicknesses are varied.

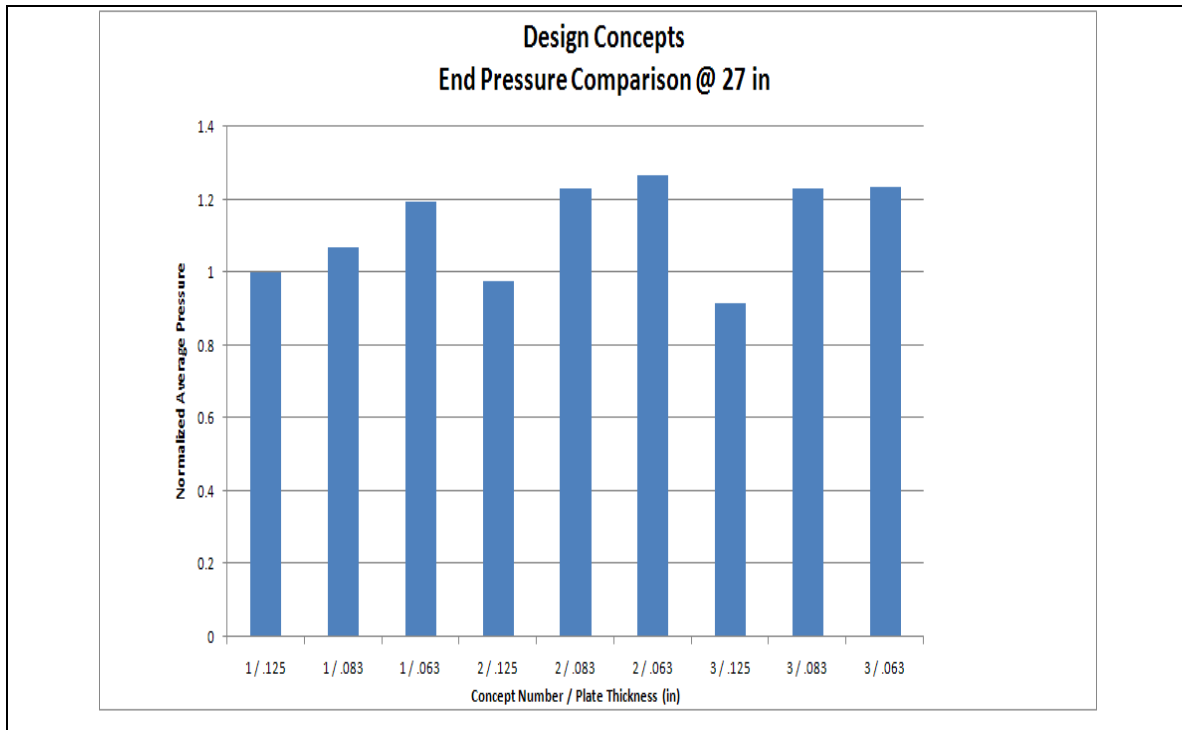


Figure 2.3-4 Bar Chart Showing Comparisons of the Three Concepts and Strike Plate Thicknesses

Concept 2 appears to show the most increase in peak pressure, with the 0.063 inch thick strike plate showing the most marked increase.

Appendix A contains an abbreviated version of the LSDYNA input file that was used to study concept 1.

In addition to the investigation of the three concepts, a study was undertaken to examine the effects of increasing the water tank diameter on the resulting pressure pulse at the test section. This study was accomplished while holding the present air gun and strike plate thicknesses constant. This led to the examination of two (2) concepts:

1. Keep the test section diameter as it is now, but remove the flare section.
2. Double the water tank diameter.

Figure 2.3-5 shows the LSDYNA predicted pressure pulse at a location 27 inches downstream from the strike plate with the current configuration (flare in place).

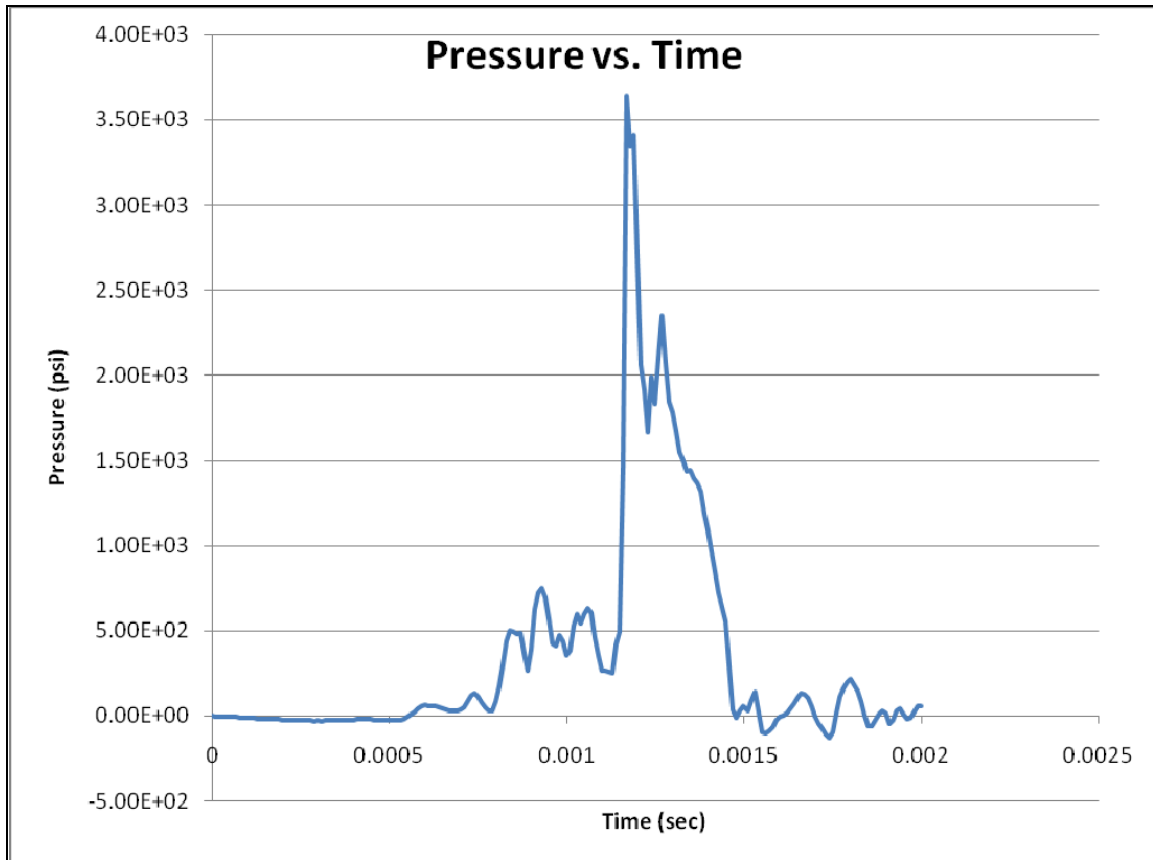


Figure 2.3-5 LSDYNA Predicted Pressure Pulse of Current Hydrodynamic Ram Simulator Configuration With Flare

Figure 2.3-6 shows the LSDYNA predicted pressure pulse at a location 27 inches downstream from the strike plate with the flare removed.

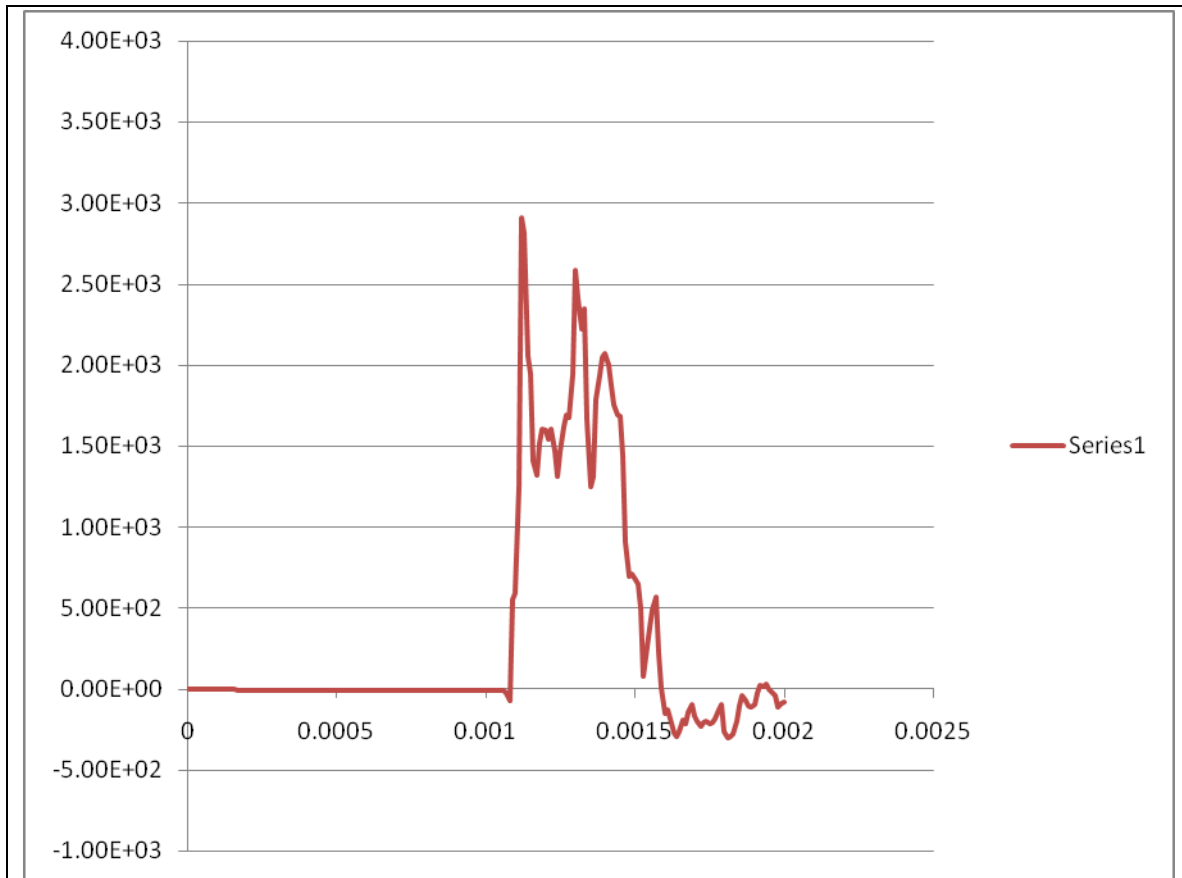


Figure 2.3-6 LSDYNA Predicted Pressure Pulse of Current Hydrodynamic Ram Simulator Configuration With No Flare

Figure 2.3-7 shows the LSDYNA predicted pressure pulse at 27 inches downstream of the striker plate, where the current configuration (with the flare) is compared with the current configuration without the flare. Note that the peak pressure is reduced by approximately 15%, but the pulse width is increased, so that the resulting impulse is approximately the same for both cases.

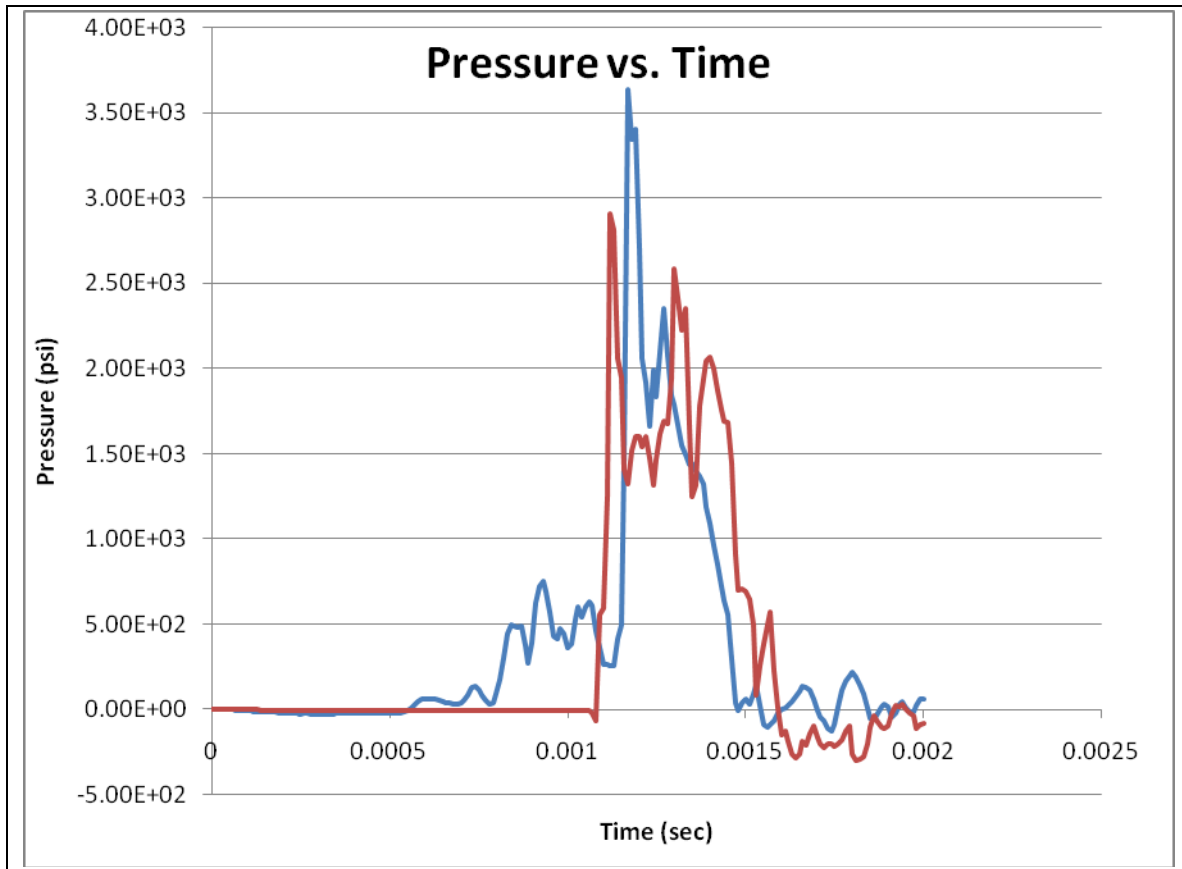


Figure 2.3-7 LSDYNA Predicted Pressure Pulse of Current Hydrodynamic Ram Simulator Configuration With and Without Flare

Figure 2.3-8 shows the LSDYNA predicted pressures for each of the cases examined. Note that the 2xD case shows peak pressure approximately 1/3 that of the 1xD case.

One key observation can be made from this figure. If one focuses on the slope of the pressure rise, shortly after 0.001 seconds, one sees that although the peak pressure is reduced, the rate of pressure rise is nearly the same for each case. This is important, since the strain rate that is introduced into the joint specimen is controlled by the loading rate that is applied. It is encouraging to see that the model is predicting nearly identical loading rates for each case.

In an attempt to understand why the pressure pulse looks so noisy, simulations using CTH[2] (axisymmetric with very fine mesh) were run with a rigid as well as an elastic wall. Figure 2.3-9 shows pressure pulse contour of the rigid wall case at 0.0005 seconds after puck impact. The key observation of this figure is the three dimensional character of the resulting pressure pulse. When the puck hits the striker plate, a hemispherically

shaped pressure pulse forms and begins propagating into the water column. This pulse quickly interacts with the cylindrically shaped side wall of the tank and reflects from all points along the wall that are impinged upon. This reflection then travels towards the centerline of the tank, where it again reflects, thus forming the X or diamond shaped structure that is observed in the figure. This continued reflection process continues down the full length of the cylindrical water tank. It should be noted as well that the reflected pulses are traveling in water through which the initial pressure pulse has already passed. This means that the reflections are traveling at a higher speed than the initial pulse and tend to “catch up” as they travel down stream. Furthermore, since water is not perfectly incompressible, there is some pressure reduction as the waves travel down the water column.

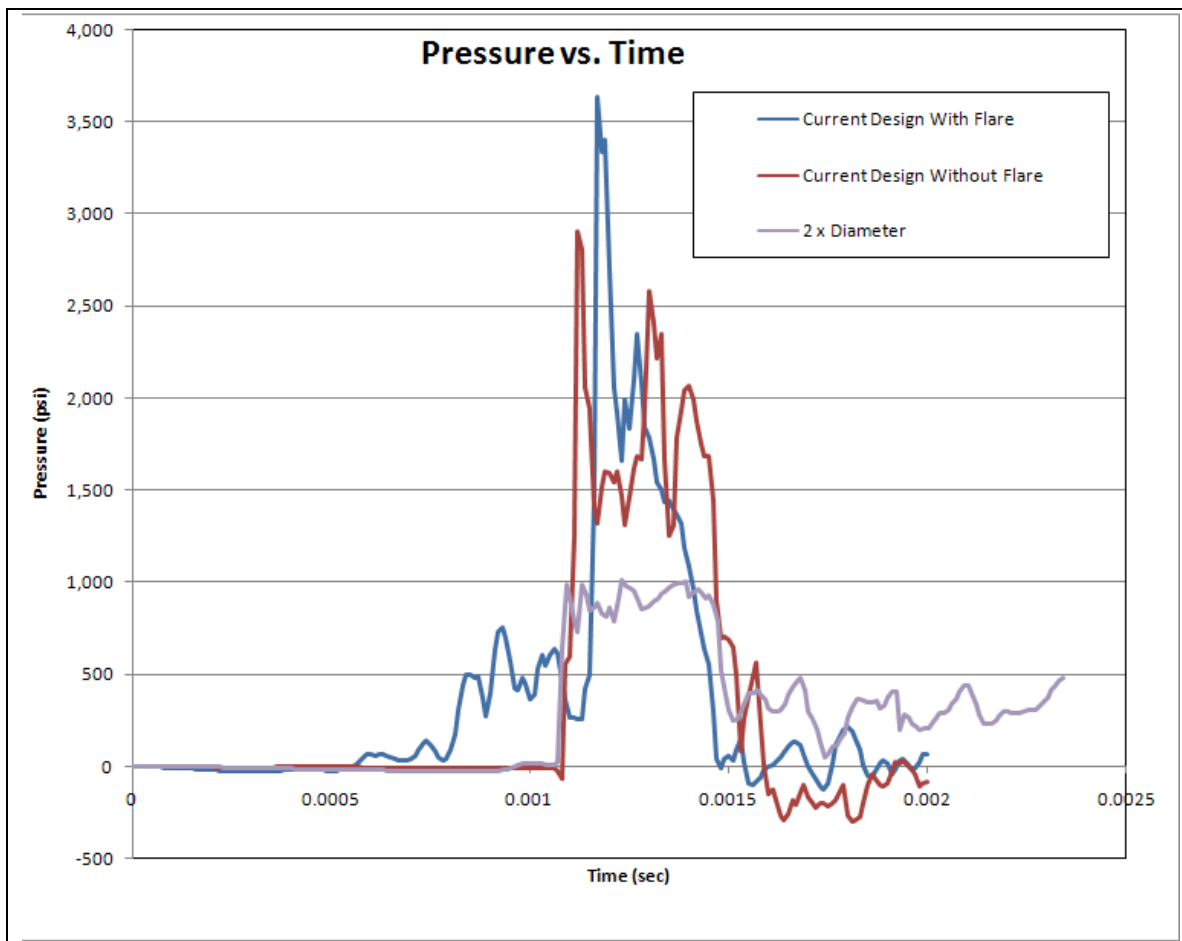


Figure 2.3-8 LSDYNA Predicted Pressure Pulse of Current Hydrodynamic Ram Simulator Configuration With and Without Flare and 2 x D

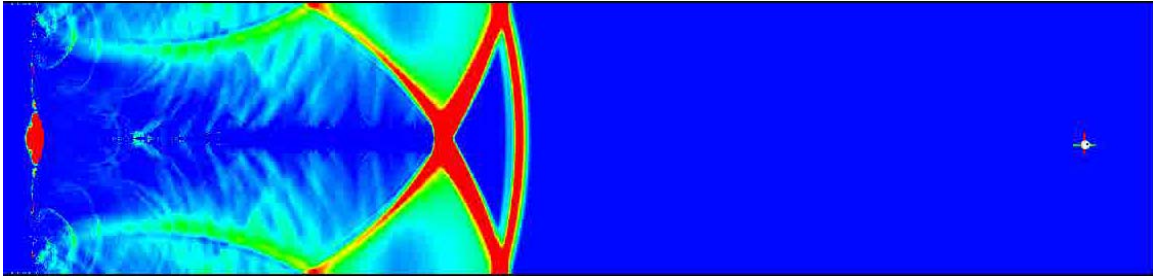


Figure 2.3-9 CTH Predicted Pressure Pulse in the 2 x D Configuration (rigid walls)

Figure 2.3-10 shows pressure pulse contour of the elastic wall case at 0.0005 seconds after puck impact. The key observation of this figure is the presence of waves traveling down the elastic wall (at the wave speed of steel) that interact with the water ahead of the initial pressure pulse formed by the puck impact. These waves reflect, interact, combine and cancel one another as well as the major pulse. The result is a very complex 3 dimensional wave pattern resulting at the test section.

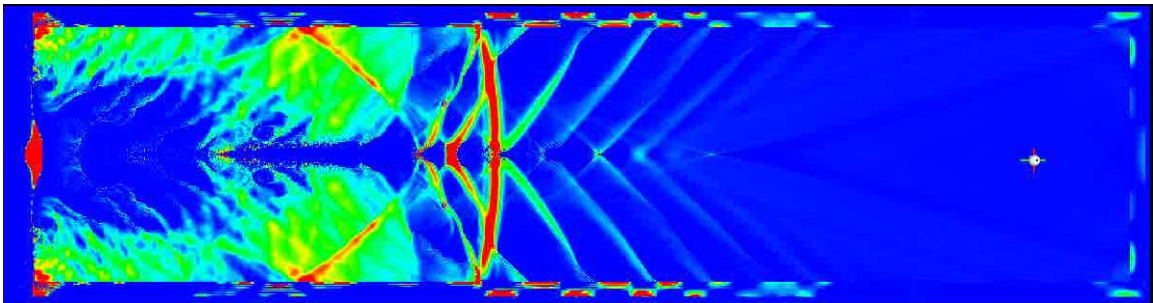


Figure 2.3-10 CTH Predicted Pressure Pulse in the 2 x D Configuration (elastic walls)

Appendix B contains a full version of the CTH input file that was used to perform these simulations.

2.4 Joint Analyses Using LSDYNA

Figure 2.4-1 shows an image of the LSDYNA model of the current Hydrodynamic Ram Simulator with the flared section and a generic joint installed. Note that the image shows the air surrounding the Hydrodynamic Ram Simulator in a semi-transparent manner so that the internal structures can be visualized.

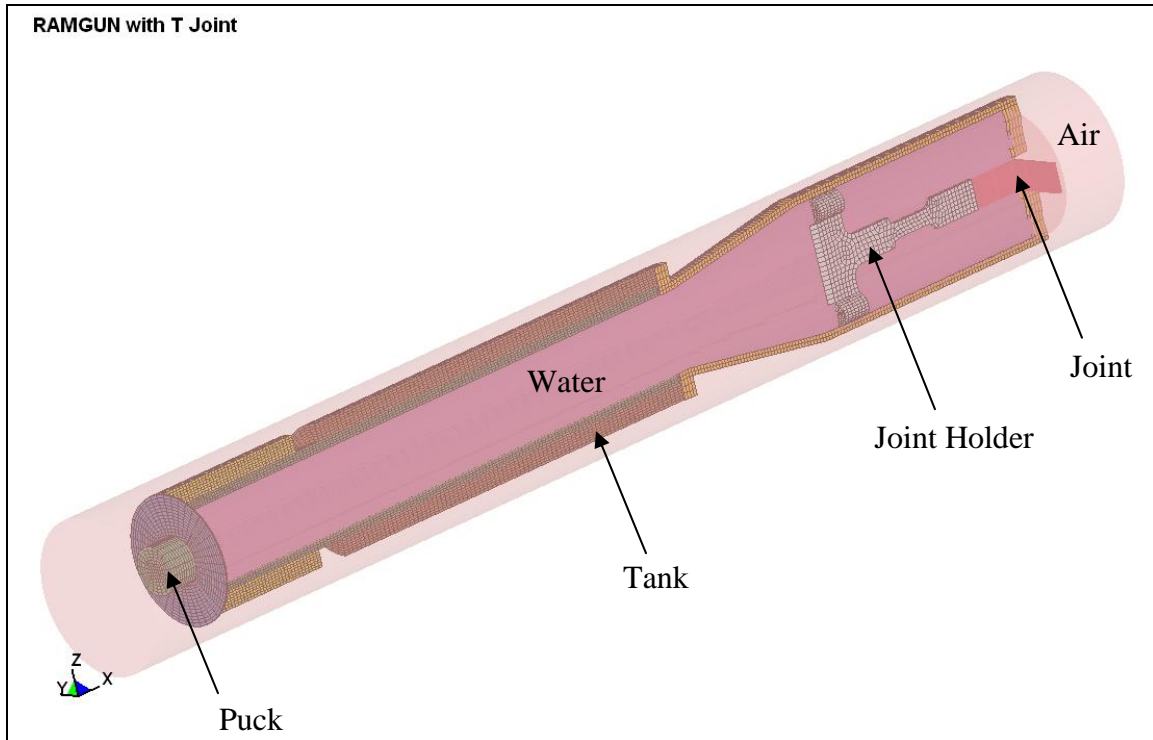


Figure 2.4-1 LSDYNA Model of Current Hydrodynamic Ram Simulator with Flare and Joint

This current configuration was modeled with the joint installed so that it could be used as a baseline for comparison with possible improvements: 1.) keep the test chamber diameter the same, but eliminate the flare and 2.) increase the test chamber diameter by a factor of 2.

Figure 2.4-2 shows a cross section of the joint (red) after the pressure pulse has passed. Note that the joint is fully damaged and has failed.

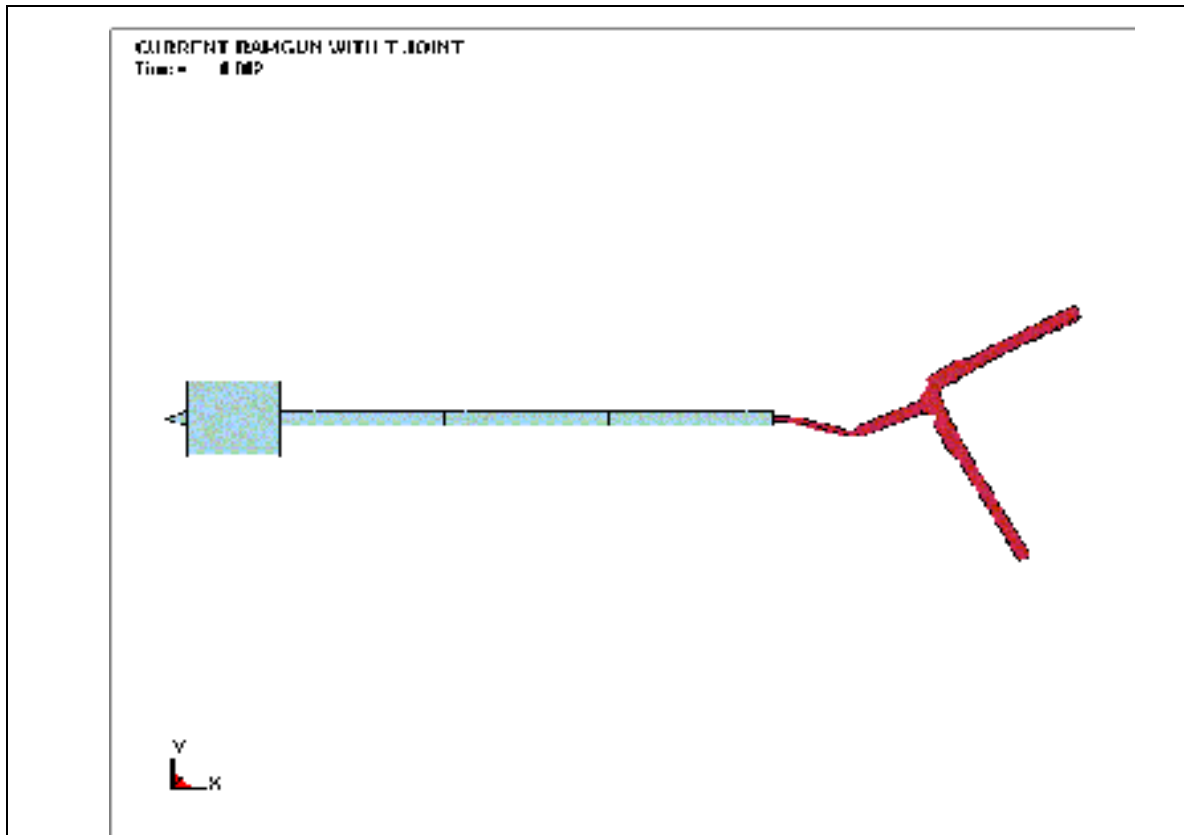


Figure 2.4-2 Joint Damage in Current Hydrodynamic Ram Simulator

Figure 2.4-3 shows the LSDYNA model of the current Hydrodynamic Ram Simulator with a generic joint installed and the flared section removed.

Figure 2.4-4 shows a cross section of the joint (red) after the pressure pulse has passed. Note that the joint is fully damaged and has failed.

Figure 2.4-5 shows the LSDYNA model of the current Hydrodynamic Ram Simulator with a generic joint installed and the flared section removed.

Figure 2.4-6 shows a cross section of the joint (red) after the pressure pulse has passed. Note that the joint is fully damaged and has failed.

In each case, the models indicate that the generic joint fails. This means that, although the peak pressure decreases as modifications to the Hydrodynamic Ram Simulator are made, there still is enough excess energy generated to fail the joint.

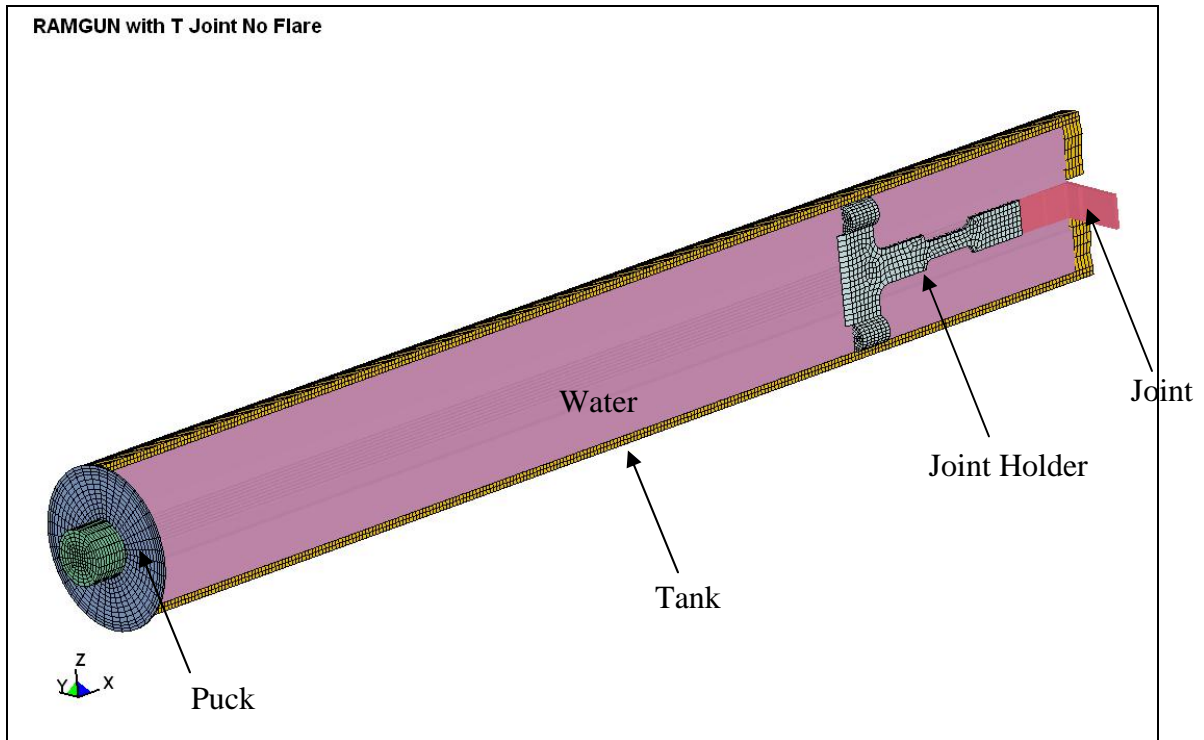


Figure 2.4-3 LSDYNA Model of Hydrodynamic Ram Simulator with no Flare and Joint (1.0 x D)

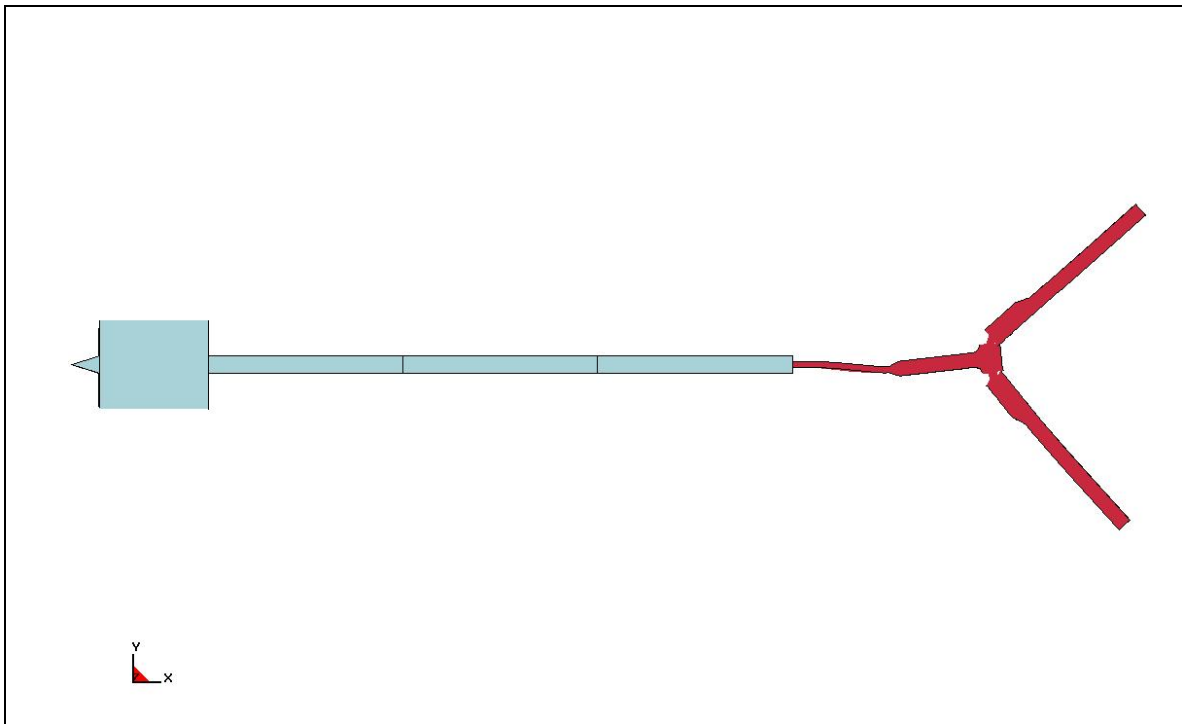


Figure 2.4-4 Joint Damage in Current Hydrodynamic Ram Simulator with Flare Removed

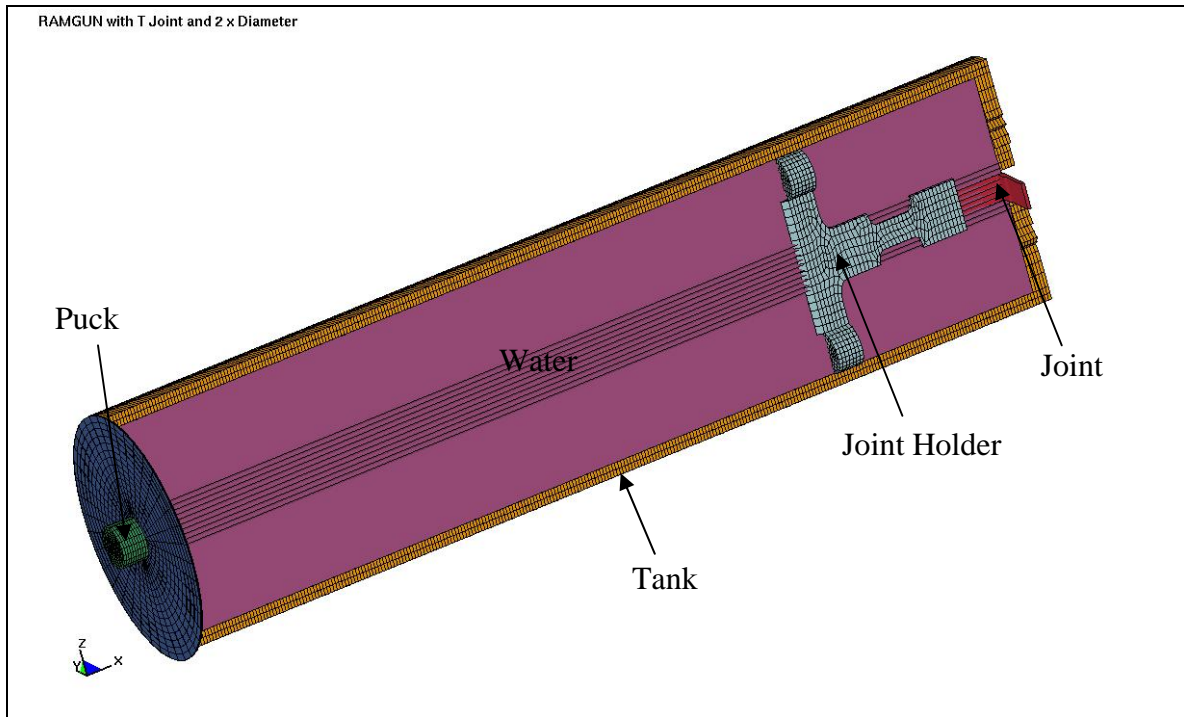


Figure 2.4-5 LSDYNA Model of Hydrodynamic Ram Simulator with no Flare and Joint (2 x D)

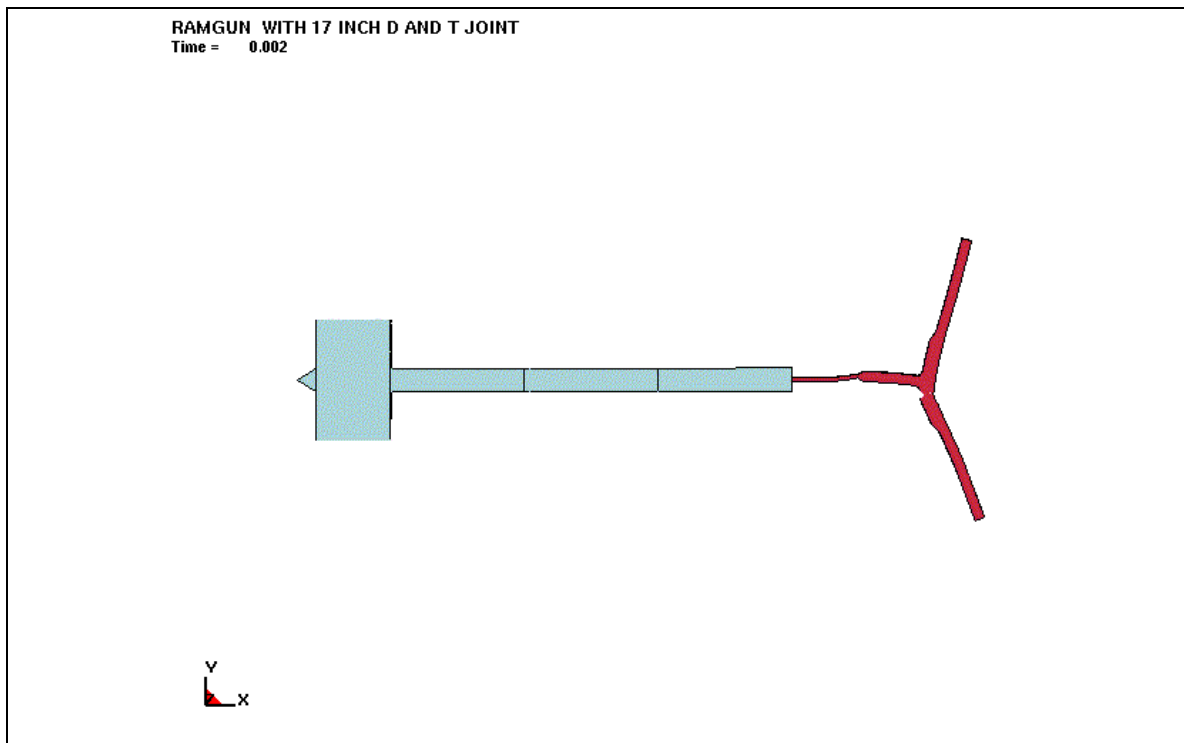


Figure 2.4-6 Joint Damage in Hydrodynamic Ram Simulator with 2 x Diameter

2.5 Demonstration-Validation of the Hydrodynamic Ram Simulator.

The demonstration-validation of the hydrodynamic ram simulator was not completed under this JASPO project. It will be done by BlazeTech as part of their Phase II SBIR effort.

3.0 Summary

During the performance of this effort, RHAMM Technologies, LLC, cooperated with BlazeTech to examine several design changes to the Hydrodynamic Ram Simulator. RHAMM's role was to perform 3D LSDYNA analyses of the water column and provide pre-test predictions of how three different concepts would compare to one another.

In addition, 3D LSDYNA analyses were performed to examine the effects of eliminating the flared section, while keeping the current test section diameter constant and increasing the diameter by a factor of two. As part of those studies, axisymmetric CTH runs were also performed in order to better understand the 3D nature of the pressure pulse as well as the influence of elastic tank walls.

Finally, RHAMM performed 3D LSDYNA predictions of how generic aircraft joints would respond to modifications to the water column, including removal of the flare and increasing the test section diameter.

4.0 Conclusions and Recommendations

The results obtained from the LSDYNA and CTH simulations of the water column lead to the following conclusions:

4.1.1 Conclusions

1. Of the three concepts being considered for modifications of the energy introduction to the water column, concept 2 with striker plate thickness of 0.063" shows the most promise.
2. Removing the flare section and increasing the diameter of the water column by a factor of 2 greatly reduces the peak pressure of the pulse at the test section. However, the initial rate of pressure rise in the associated pulses appears to be the

same in each case. This is important in joint testing, because the strain rate within the joint is dependent on the loading rate.

3. Although removing the flare and increasing the diameter of the water column results in a reduction in peak pressure, it appears from the analyses that there is still sufficient impulse imparted to a typical generic fighter aircraft joint to lead to joint failure. The reader is cautioned, however, that the analysis was done on a generic fighter aircraft joint and may not be representative of all fighter aircraft joints. Furthermore, cargo aircraft joints are larger and stronger than fighter joints. If cargo aircraft joints are to be tested, then the impulses at the test section will need to be increased.
4. The CTH runs clearly show that there will always be wave interactions as a result of using steel in conjunction with a cylindrically shaped water column.

4.1.2 Recommendations

1. Concept 2 with striker plate thickness of 0.063" is recommended as a way to increase the peak pressure within the water column.
2. Increase the water column diameter by a factor of 2, while maintaining the current air gun configuration (puck diameter, thickness, barrel length, etc) and perform characterization tests at the test section. Compare pressures with those predicted by the simulations. Place a generic cargo aircraft joint in the 2 x D test section and perform a test to see if the current air gun configuration can deliver enough impulse to fail the joint.
3. If the generic joint testing recommended above is not successful, modify the air gun to increase the energy imparted to the water column. Any or all of the modifications examined in section 2.1.1 are recommended

5.0 References

1. "LSDYNA User's Manual – Version 970", April, 2003.
2. "CTH User's Manual and Input Instructions Version 8.0", D. A. Crawford, R. L. Bell, C. W. Bruner, M. G. Elrick, E. S. Hertel, Jr., R. G. Schmitt, S. C. Schumacher, S. A. Silling, J. S. Simmons and P. A. Taylor, Sandia National Laboratories, March 22, 2007.

6.0 Appendices

6.1 Appendix A

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$#      sfs      sfm      sst      mst      sfst      sfmt      fsf
vsf
$      1.000000      1.000000      0.000      0.000      1.000000      1.000000      1.000000
1.000000
$#      soft      sofsc1      lcidab      maxpar      sbopt      depth      bsort
frcfrq
$      1      0.100000      0      1.025000      0.000      2      0
1
$#      penmax      thkopt      shlthk      snlog      isym      i2d3d      sldthk
sldstf
$      0.000      0      0      0      0      0      0.000
0.000
$#      igap      ignore      dprfac      dtstif      unused      unused      flangl
$      1
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID
$#      cid
title
      7striker plate to gasket
$#      ssid      msid      sstyp      mstyp      sboxid      mboxid      spr
mpr
$#      6      36      3      3
$#      fs      fd      dc      vc      vdc      penchk      bt
dt
$      0.000      0.000      0.000      0.000      0.000      0
0.0001.0000E+20
$#      sfs      sfm      sst      mst      sfst      sfmt      fsf
vsf
$      1.000000      1.000000      0.000      0.000      1.000000      1.000000      1.000000
1.000000
$#      soft      sofsc1      lcidab      maxpar      sbopt      depth      bsort
frcfrq
$      1      0.100000      0      1.025000      0.000      2      0
1
$#      penmax      thkopt      shlthk      snlog      isym      i2d3d      sldthk
sldstf
$      0.000      0      0      0      0      0      0.000
0.000
$#      igap      ignore      dprfac      dtstif      unused      unused      flangl
$      1
*PART
$# title
Tank_Inner
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
$      3      20      35
*SECTION_SOLID_TITLE
Lagrangian
$#      secid      elform      aet
$      20      1
*MAT_RIGID_TITLE
Rigid
$#      mid      ro      e      pr      n      couple      m
alias

```

```

      35 7.3300E-4 2.9000E+7 0.320000      0.000      0.000      0.000
$#      cmo      con1      con2
      0.000      0      0
$#lco or a1      a2      a3      v1      v2      v3
      0.000      0.000      0.000      0.000      0.000      0.000
*PART
$# title
Collar
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
      4      20      35
*PART
$# title
Tank_Outer
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
      5      20      35
*PART
$# title
Gasket
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
      6      20      7
*MAT_ELASTIC
$#      mid      ro      e      pr      da      db      not used
      7 7.3300E-4 2.9000E+7 0.320000
*PART
$# title
water
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
      16      1      9      10      1
*SECTION_SOLID_TITLE
Eulerian
$#      secid      elform      aet
      1      12
*MAT_NULL_TITLE
Water
$#      mid      ro      pc      mu      terod      cerod      ym
pr
      9 1.0000E-4-6000.0000 2.5700E-7
*EOS_GRUNEISEN
$#      eosid      c      s1      s2      s3      gamao      a
e0
      10 58267.000 2.560000 -1.986000 0.226800 0.500000
$#      v0
      0.000
*HOURLGLASS
$#      hgid      ihq      qm      ibq      q1      q2      qb/vdc
qw
      1      1 1.0000E-5      0 1.500000 0.060000 0.100000
0.100000
*PART
$# title
flared end
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid

```

```

17      20      35
*PART
$# title
air
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
18      1      9      10      1
*PART
$# title
striker plate
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
36      23      8
*SECTION_SHELL_TITLE
striker plate
$#      secid      elform      shrf      nip      propt      qr/irid      icomp
setyp
23      2      0.000      0      1      0      0
1
$#      t1      t2      t3      t4      nloc      marea      idof
edgset
0.125000 0.125000 0.125000 0.125000
*PART
$# title
puck
$#      pid      secid      mid      eosid      hgid      grav      adpopt
tmid
37      20      11
*MAT_PLASTIC_KINEMATIC
$#      mid      ro      e      pr      sigy      etan      beta
11 1.3200E-4 4.5000E+5 0.330000 18000.000 10000.000
$#      src      srp      fs      vp
0.000      0.000 0.600000
*SECTION_SHELL
$#      secid      elform      shrf      nip      propt      qr/irid      icomp
setyp
2      16 1.000000      3      1
$#      t1      t2      t3      t4      nloc      marea      idof
edgset
0.030000 0.030000 0.030000 0.030000
*SECTION_SOLID
$#      secid      elform      aet
21      1
*SECTION_SOLID
$#      secid      elform      aet
22      1
*MAT_PIECEWISE_LINEAR_PLASTICITY
$#      mid      ro      e      pr      sigy      etan      fail
tdel
8 7.4000E-4 2.8600E+7 0.310000 80000.000 5.0000E+6 0.000
1.0000E-9
$#      c      p      lcss      lcsr      vp
0.000      0.000      0      0      0.000
$#      eps1      eps2      eps3      eps4      eps5      eps6      eps7
eps8
0.000 0.003000 0.005000 0.006000 0.009000 0.015000 0.200000

```

\$#	es1	es2	es3	es4	es5	es6	es7	es8
	80000.000	90000.000	1.0000E+5	1.1000E+5	1.2000E+5	1.3000E+5	1.5000E+5	
*MAT_PLASTIC_KINEMATIC								
\$#	mid	ro	e	pr	sigy	etan	beta	
	29	1.4610E-4	6.0000E+6	0.330000	90000.000	5.0000E+5		
\$#	src	srp	fs	vp				
	0.000	0.000	0.030000					
*MAT_PLASTIC_KINEMATIC_TITLE								
Polyethylene								
\$#	mid	ro	e	pr	sigy	etan	beta	
	31	8.8820E-5	53000.000	0.350000	3420.0000	50000.000		
\$#	src	srp	fs	vp				
	0.000	0.000	0.040000					
*MAT_ELASTIC								
\$#	mid	ro	e	pr	da	db	not used	
	32	1.000000	1.000000	0.250000				
*MAT_ELASTIC_TITLE								
T-joint								
\$#	mid	ro	e	pr	da	db	not used	
	33	1.4610E-4	6.0000E+6	0.330000				
*MAT_ELASTIC								
\$#	mid	ro	e	pr	da	db	not used	
	34	1.000000	1.000000	0.300000				
*INITIAL_VOID_PART								
\$HMALE	COLOR-NAME	28InitialVoid_19						
\$#	pid							
	18							
*INITIAL_VELOCITY_GENERATION								
\$#nsid/pid	styp	omega	vx	vy	vz			
	37	2	0.000	10330.000				
\$#	xc	yc	zc	nx	ny	nz	phase	
	0.000	0.000	0.000	0.000	0.000	0.000	0	
*SET_PART_LIST_TITLE								
Euler								
\$#	sid	da1	da2	da3	da4			
	2							
\$#	pid1	pid2	pid3	pid4	pid5	pid6	pid7	
pid8	16	18						
*SET_PART_LIST_TITLE								
Lagrange_tank								
\$#	sid	da1	da2	da3	da4			
	3							
\$#	pid1	pid2	pid3	pid4	pid5	pid6	pid7	
pid8	3	6	17	36				
*SET_SEGMENT_TITLE								
gasket inside								
\$#	sid	da1	da2	da3	da4			
	3							
\$#	n1	n2	n3	n4	a1	a2	a3	
a4	83976	83980	83979	83975				
	83983	83985	83980	83976				
	83980	83994	83993	83979				

```

.
.
    923214    923223    923224    923215
    923215    923224    923225    923216
    923216    923225    923226    923217
*SET_SEGMENT_TITLE
gasket outside
$#      sid      da1      da2      da3      da4
      5
$#      n1      n2      n3      n4      a1      a2      a3
a4
      84117      84119      84118      84116
      84116      84118      84121      84120
      84119      84126      84125      84118
.
.
.
    84162      89643      89644      84163
    89640      89572      89578      89643
    89643      89578      89580      89644
*SET_SEGMENT_TITLE
inner tank to gasket
$#      sid      da1      da2      da3      da4
      6
$#      n1      n2      n3      n4      a1      a2      a3
a4
      4976      4978      4977      4975
      4975      4977      4980      4979
      4979      4980      4982      4981
.
.
.
    4978      37831      37830      4977
    4977      37830      37832      4980
    4980      37832      37833      4982
    4982      37833      37834      4984
*SET_SOLID
$#      sid
      1
$#      k1      k2      k3      k4      k5      k6      k7
k8
      721175      716535      711895      707255      702615      697975      693335
688695
      684055      679415      674775      670135      663175      663205      662775
662805
      662835      662865
*CONSTRAINED_LAGRANGE_IN_SOLID
$#  slave  master  sstyp  mstyp  nquad  ctype  direc
mcoup
      3      2      0      0      2      4      2
1
$#  start      end      pfac      fric      frcmin      norm      normtyp
damp
      0.000      0.000  0.300000  0.000  0.300000
$#      cq      hmin      hmax      ileak      pleak      lcidpor      nvent
blockage
      0.010000      0.000      0.000      1  0.010000

```

```

*DAMPING_GLOBAL
$#      lcld      valdmp      stx      sty      stz      srx      sry
srz
      0  0.010000
*ELEMENT_SOLID
$#      eid      pid      n1      n2      n3      n4      n5      n6
n7      n8
      3511      3      4685      4686      4687      4688      4689      4690
4691      4692
      3512      3      4686      4693      4694      4687      4690      4695
4696      4691
      3513      3      4693      4697      4698      4694      4695      4699
4700      4696
.
.
.
1663387      36  923258  923267  923268  923259
1663389      36  923259  923268  923269  923260
1663391      36  923260  923269  923270  923261
1663393      36  923261  923270  923271  923262
*NODE
$#      nid      x      y      z      tc
rc
      1      0.000      4.3472767      0.6109699
      2      0.000      4.1845899      0.5881058
      5      0.000      4.3899999
.
.
.
937213      42.0000000      -0.6360209      -2.1168311
937214      42.0000000      -0.3858445      -2.2910023
*END

```

6.2 Appendix B

```

*
*eor*cgenin
*
2d-ramgun
*
control
  mmp
endcontrol
*****
*****
*
* material strength records
*
epdata
  vpsave
  matep 2
  johnson-cook steel
  jfrac steel
  jfpf0 -15.0e9

```

```

mix 3
ende
*
mesh
  block geometry 2dc type e
    x0=0.0
    x1 n=108 dxf=.2 w=21.6
    endx
    y0=-5.38226
    y1 n=1854 dyf=.1 w=185.4
    endy
  endblock
endmesh
*
insertion of material
  block 1
    package puck
    material 1
    numsub 2
    xvel 0.
    yvel 30000.
  *
    yvel 0.
    insert box
      p1 0. -5.38226
      p2 4.191 -0.30226
    endinsert
  endpackage
  package striker
  material 2
  numsub 2
  xvel 0.
  yvel 0.
  insert box
    p1 0.00 -0.30226
    p2 21.6 0.00
  endinsert
  endpackage
  package water
  material 3
  numsub 2
  xvel 0.
  yvel 0.
  insert box
    p1 0. 0.00
    p2 21.6 185.42
  endinsert
  endpackage
endblock
endinsertion
*
eos
  mat1 mgrun polyethylene
  mat2 sesame steel_4340

```

```

*   mat2 mgrun user t0=0.5 r0=7.896 cs=4.569e5 s1=1.490 g0=2.17
cv=5.18e10 *340_SS
    mat3 sesame water
*   mat4 sesame air
endeos
*
tracer
    add 0.00 169.0 fixed xyz
    add 2.00 169.0 fixed xyz
    add 4.00 169.0 fixed xyz
    add 6.00 169.0 fixed xyz
    add 8.00 169.0 fixed xyz
    add 10.0 169.0 fixed xyz
endtracer
*
*eor*cthin
*
    2d-ramgun
*
control
    tstop=2.00e-3
*   cpshift=900.
    rdumpf=3600
    ntbad=1e30
endcontrol
*
cellthermo
    mmp
endcell
*
convct
    convect=1
    interface=high
endc
*
edit
    shortt
        tim=0. dt=5.0e-6
    ends
    longt
        tim=0. dt=5.0e-6
    endl
endedit
*
mindt
    time=0. dtmin=1.0e-11
    time=20.0e-6 dtmin=1.0e-10
endm
*
boundary
    bhydro
        block=1
        bxbot 0
        bxtop 0

```

```

        bybot 2
        bytop 0
    endb
endh
endb
*
spy
    PlotTime(0.0,1.0e-5);
    SaveTime(0.0,1.0e-5);
    Save("VOLM,P,DENS,VX,VY,VZ");
    ImageFormat(1024, 768, IN_MEMORY, JPEG);
    define main()
    {
    }
    SaveHis("GLOBAL,P,VOLM");
    SaveTracer(ALL);
    HisTime(0,1.0e-6);
endspy
*eor*

```